DEVELOPMENT OF FRAMEWORK FOR THE ADOPTION OF CONSTRUCTION 4.0 FOR CONSTRUCTION PROJECTS

Synopsis of the PhD Thesis

Submitted by

Pallavi S. Dhamak

(Roll No.: P003)

Department of Technology Management

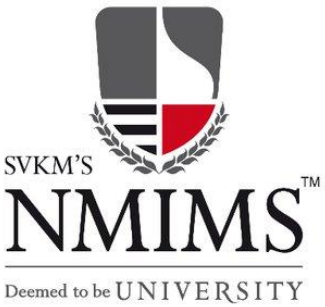
Supervisor(s)

Dr. Abhay Kumar (Research Guide)

Dr. Anand Daftardar (Research Co-Guide)

submitted in partial fulfilment of the requirements of

DOCTOR OF PHILOSOPHY (Technology Management)



MUKESH PATEL SCHOOL OF TECHNOLOGY MANAGEMENT & ENGINEERING

SVKM'sNARSEE MONJEE INSTITUTE OF MANAGEMENT STUDIES (Declared as Deemed-to-be University Under Section 3 of the UGC Act, 1956)

V. L. Mehta Road, Vile Parle (West)

MUMBAI –400056

TABLE OF CONTENTS

SECTION NO.	TITLE	PAGE NO.
1	ABSTRACT	1
2	INTRODUCTION 2.1 Research Motivation 2.2 Problem Statement	1
3	RESEARCH OBJECTIVES	2
4	LITERATURE REVIEW 4.1 Construction 4.0 and its Enabling Technologies 4.2 Growth of Construction 4.0 4.3 Barriers associated with Adoption of Construction 4.0 4.4 Construction 4.0 Innovation Ecosystem and its Perspectives 4.5 Researcher's Contribution Analysis 4.6 Exploratory Observations from Industry and Academia 4.6.1 Construction Site Visits 4.6.2 Academic Observations: Visit to the University of Malaga, Spain 4.7 Research Gaps	3
5	RESEARCH METHODOLOGY	17
6	CONTRIBUTIONS 6.1 Determination of Current Adoption Scenario of Construction 4.0 Enabling Technologies 6.1.1 Understanding of the Construction 4.0 Concept in Construction Industries 6.1.2 Spread of Construction 4.0 Enabling Technologies 6.1.3 Motivating Factors for Construction 4.0 Implementation 6.1.4 Impact of Construction 4.0 Enabling Technologies on Construction Processes 6.1.5 Outcomes of Expert Interview 6.1.6 Validation of Hypotheses 6.1.7 Reasons for Low Adoption of Construction 4.0 Enabling Technologies 6.1.8 Strategic Framework for Construction 4.0 Implementation 6.2 Analysis of Barriers associated with the Adoption of Construction 4.0 6.2.1 Strategies to Address the Identified Barriers 6.2.2 Effectiveness of Proposed Strategies 6.2.3 Hypothesis Validation 6.2.4 Barrier Management Framework	19

6.3 Analysis of Perspectives and Components of Construction 4.0 Innovation Ecosystem Framework
6.3.1 Construction 4.0 Innovation Ecosystem Framework
6.3.2 Bridging Construction 4.0 and 5.0: Academia Extensions

7 CONCLUSIONS 45

8 FUTURE SCOPE 47

9 PUBLICATIONS 48

10 REFERENCES

LIST OF FIGURES

FIGURE NO.	NAME OF FIGURE	PAGE NO.
4.1	Perspectives Adapted from the Quadruple Helix Model of Innovation	11
5.1	Research Methodology Flow Chart	18
5.2	Hypotheses Conceptual Framework	18
6.1	Understanding of Construction 4.0	20
6.2	Spread of Construction 4.0 Enabling Technologies	21
6.3	Motivating Factors for Construction 4.0 Implementation	22
6.4	Impact of Construction 4.0 Enabling Technologies - Economic Dimension	24
6.5	Impact of Construction 4.0 Enabling Technologies - Environmental Dimension	25
6.6	Impact of Construction 4.0 Enabling Technologies - Social Dimension	25
6.7	Reasons for Low Adoption of Construction 4.0 Enabling Technologies	29
6.8	Strategic Framework for Construction 4.0 Implementation	30
6.9	Barrier Management Framework	39
6.10	The Visualization of the Interactions among Perspectives of Construction 4.0 Innovation Ecosystem	41
6.11	Construction 4.0 Innovation Ecosystem Framework	43

LIST OF TABLES

TABLE NO.	NAME OF TABLE	PAGE NO.
4.1	Construction 4.0 Enabling Technologies	3
4.2	Construction 4.0's Growth	4
4.3	Barriers Linked to the Adoption of Construction 4.0	7
4.4	List of Perspectives and their Components	12
6.1	Impact of Construction 4.0 Enabling Technologies	23
6.2	P-value and Decision	27
6.3	Ranking of Barriers	33
6.4	Proposed Strategies to Mitigate the Barriers	35
6.5	Effectiveness Index of Proposed Strategies	37
6.6	Summary of P-value	38
6.7	T-Matrix Calculation	40
6.8	Effects and Ranking of Perspective's Components	42
7.1	Research Objectives vs. Research Deliverables	46

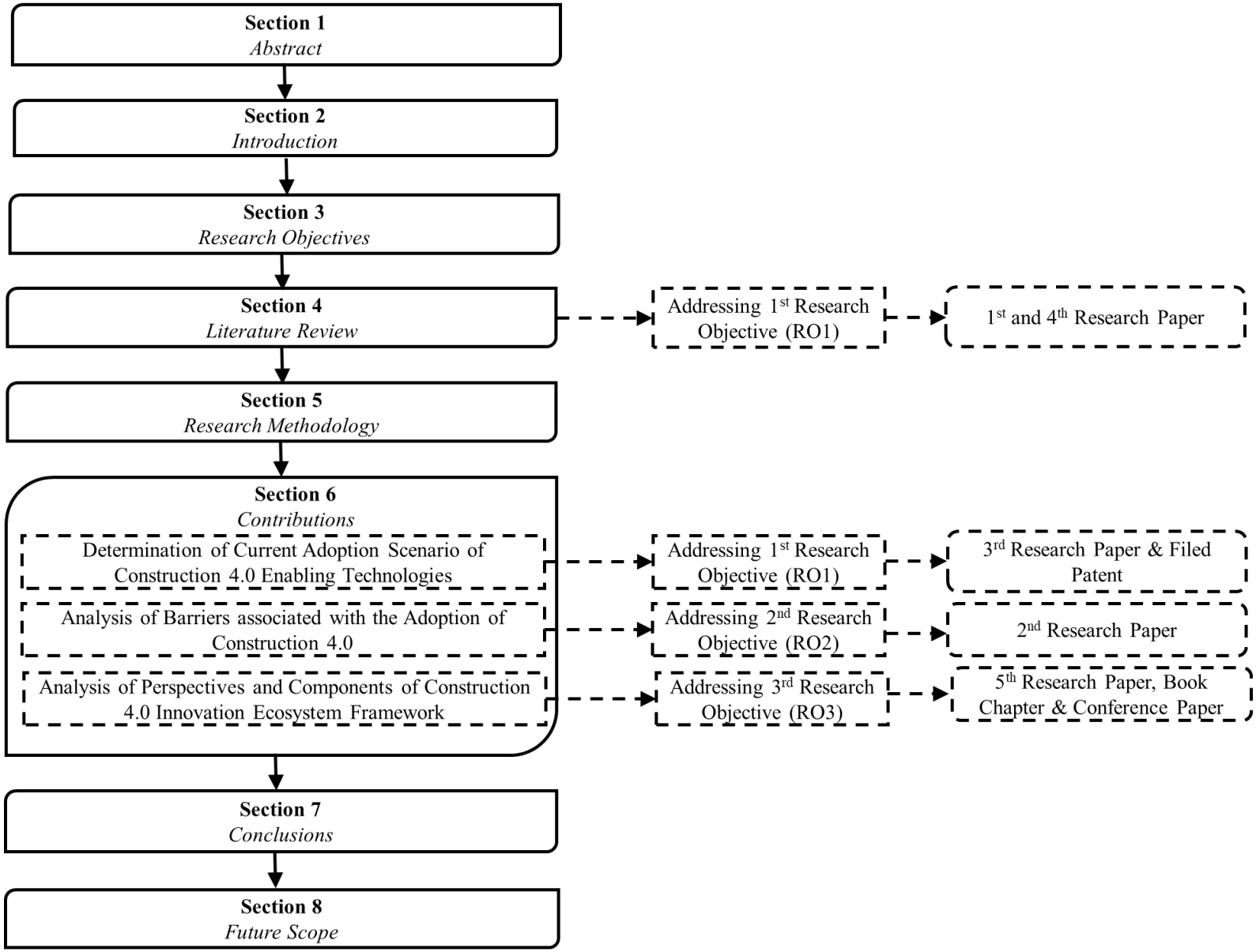


Figure (a): Structure of the Synopsis

1. ABSTRACT

The construction industry is undergoing a digital transformation with the advent of Construction 4.0, a concept that integrates advanced technologies such as Building Information Modeling (BIM), Internet of Things (IoT), Artificial Intelligence (AI), robotics, and data analytics. This research explores the current adoption scenario of Construction 4.0 enabling technologies, identifies key barriers, and proposes strategic frameworks to enhance the implementation of Construction 4.0 technologies in the construction sector. Through a comprehensive literature review, expert interviews, and survey-based data collection from 43 industries and 129 professionals, it is found that BIM emerged as the most adopted technology, while cloud computing, big data analytics, and cybersecurity remain underutilized. A list of barriers associated with the adoption of Construction 4.0 is identified and prioritized by using the Multi-Criterion Decision-Making (MCDM) method, and a barrier management framework is proposed. Furthermore, the research establishes the causal relationships among academia, industry, government, and civil society within a Construction 4.0 innovation ecosystem. The study validates hypotheses that understanding the Construction 4.0 concept, motivating factors, and barriers significantly affect the adoption of Construction 4.0. A strategic framework and an ecosystem model are proposed to facilitate successful implementation. This research contributes to theory and practice by offering holistic insights and actionable recommendations for stakeholders to navigate the digital shift in the construction industry, particularly in developing countries.

2. INTRODUCTION

The application of Industry 4.0 enabling technologies (such as Internet of Things (IoT), Artificial Intelligence (AI), and automation) in construction industry has evolved the concept called as ‘Construction 4.0’ [1-3]. It is also termed as the integration of smart materials, automation, and digital technology in the construction industry [4, 5]. The Construction 4.0 concept represents the construction industry's evolution through technological advancements, especially in the Internet of Things (IoT), artificial intelligence, robotics, and big data analytics [6-8]. This concept has revolutionized the traditional construction processes resulting in enhanced decision-making, optimized resource utilization, and improved safety protocols [9, 10]. For example, UAVs are used for surveying and inspection purposes, 3D printing is applied in construction for speedy work progress, and robots perform repetitive and hazardous tasks [11-13]. Additionally, data analytics are crucial for optimizing construction procedures and processes, reducing waste, and improving quality standards [14-16].

The GDP (Gross Domestic Product) of world is significantly influenced by the construction industry [17-19]. According to McKinsey Report 2022, the contribution of the construction sector to world’s GDP was 13% in the financial year 2020-21 [20-22]. The Economic growth of developing nations like India, Bangladesh, Pakistan, etc. has been heavily influenced by its construction sector, which has generated numerous opportunities for jobs and assembled essential and important infrastructure in the country [23, 24]. The Government of developed and developing nations has been actively supporting the construction industry sector with various initiatives, such as the Pradhan Mantri Awas Yojana (PMAY) scheme in India, Housing First scheme in USA, Green Building Initiative in Australia, Building Better Scheme in New Zealand, and Constructing a Digital Future Scheme in United Kingdom [25-27]. These

initiatives address housing, sustainability, and digital transformation in the construction industry [28-30]. Furthermore, the Government of India emphasis on developing Expressways, National highways, Airports, Railways, Harbors, Monuments, and other public infrastructure which will further help in the growth of the construction sector [31-33]. The construction sector is also expected to benefit from the ambitious goal of achieving $5 trillion in economic output by the year 2025 [34, 35].

2.1 Research Motivation

To improve decision-making and production efficiency technologies like IoT, big data, cloud computing, and augmented reality have already been successfully implemented in the manufacturing industry sector [36-38]. However, there is still limited understanding of how effective these technologies are in the construction industry sector [39-41]. Despite rapid advancements in Construction 4.0 research, much of the current literature focuses on individual technologies or regional applications, offering limited insights into how these technologies interact and are integrated within construction ecosystems globally [42-44]. From managerial viewpoints, the acceptance of Industry 4.0 initiatives in construction sector is a new concept in India as compared to other sectors like manufacturing, automotive, logistics, power sector and energy. The Indian government is looking for development of the economy and create employment opportunities by using Industry 4.0 and modern information technologies in the construction industry. However, the true fact is that Industry 4.0 in construction sector includes some challenges like data excellence and reliability, joblessness, complexity issues, less human control, and higher negative environmental influences. To tackle these challenges, we should focus on nurturing a culture of innovation, ensuring that skilled workers are available, and building robust systems to integrate technology and teamwork across the industry [45-47]. Research from China, Japan, the United States, and Germany shows that only 15% of businesses have plans to adopt Construction 4.0. It has been observed that despite the many benefits of Construction 4.0, it is not yet fully utilized in the industry. Due to the unavailability of a standard Construction 4.0 implementation framework, Developed and developing countries have struggled to explore the capabilities of Construction 4.0 in a nutshell [48-50].

2.2 Problem Statement

The construction sector harbor uncertainty regarding the concept of Construction 4.0, primarily due to a dearth of precise implementation guidelines and substantial financial investments required. As a result, the adoption level of the Construction 4.0 concept within the construction industry remains low. Therefore, it is a need of time to develop a framework to integrate the enabling technologies of Construction 4.0 to improve the performance and process of construction sector.

3. RESEARCH OBJECTIVES (ROs)

- RO1: To determine the current research and adoption scenario of Construction 4.0 enabling technologies and its impact on construction processes.
- RO2: To identify and prioritize the barriers associated with the implementation of Construction 4.0 and develop barrier management framework.
- RO3: To determine the causal relationship among the components of ecosystem of Construction 4.0 concept and develop the ecosystem framework.

4. LITERATURE REVIEW

4.1 Construction 4.0 and its Enabling Technologies

Technological advancements have revolutionized the construction sector. Efficiency, safety, and sustainability of construction processes can be enhanced by integrating digital technologies into the physical construction activities [51-56]. This is called Construction 4.0. It deals with the integration of various digital technologies i.e. Virtual and Augmented Reality (VR/AR), Building Information Modeling (BIM), Artificial Intelligence (AI), and Internet of Things (IoT), etc. to enhance safety, reduce scrap, improve construction efficiency, and optimize building performance [57-60]. The construction industry's efficiency, productivity, and safety can be enhanced by using digital technologies such as BIM, AI, 3D printing, and drones [61-63]. Construction 4.0 streamlines the workflows, reduces operational costs, and enhances the process quality. It also promotes the sustainable construction concept by encouraging the use of energy-efficient designs and sustainable materials [64-66]. Construction 4.0 focuses on enhancing the activities of traditional construction industries by using advanced digital technologies [67-69]. Table 4.1 shows the Construction 4.0 enabling technologies.

Table 4.1: Construction 4.0 Enabling Technologies

Construction 4.0 Enabling Technologies	Features	References
Internet of Things (IoT)	It provides real-time data on construction site conditions, equipment health, and worker activities.	[70-72]
AI & ML	It analyses large datasets to derive insights, identify patterns, and optimize construction processes.	[73-74]
Autonomous Robots	Autonomous robots in construction are designed to perform repetitive and labor-intensive tasks without constant human intervention.	[75-77]
Augmented Reality (AR)	It provides immersive visualization, allowing stakeholders to experience a virtual representation of construction projects.	[78-82]
3D Printing	It enables the rapid prototyping of construction components and structures, allowing for quick iterations in design.	[83-86]
Cloud Computing	It provides a centralized platform for storing and accessing project data, enabling real-time collaboration among geographically dispersed teams.	[87-90]
Cybersecurity	It enhances data security by ensuring that only authorized individuals have access to critical project resources and information.	[91-93]
Simulation	It allows the creation of virtual prototypes and models of construction projects, providing a detailed representation of the structures and environments.	[94-97]
Drones	Drones are used for aerial , aero photogrammetry, inspections, and monitoring, providing a bird's eye view of construction sites.	[98-101]

Big Data Analytics	It enables a holistic view of the construction project by consolidating information from various sources, supporting better decision-making.	[102-105]
Smart Sensors	Different parameters i.e. temperature, humidity, etc. associated with the construction activities are provided in real-time by smart sensors. Hence, it enhances the proactive decision-making ability of construction project managers.	[106-108]
Building Information Modeling (BIM)	BIM enables the creation of detailed 3D models of construction projects, and visual representation by providing a comprehensive idea.	[109-111]
Digital Twin	It enables the integration of data from sensors, IoT devices, and other sources for the real-time monitoring of construction assets.	[112-114]

4.2 Growth of Construction 4.0

Due to the increasing need for efficient and sustainable construction practices, Construction 4.0 enabling technologies are growing rapidly. The rapid advancements of Construction 4.0 enabling technologies are very essential to address the construction industry challenges. This rapid growth helps to enhance the construction industry's efficiency and productivity. Also, communication and collaboration among construction project stakeholders can be improved. Table 4.2 shows Construction 4.0's growth in chronological order.

Table 4.2: Construction 4.0's Growth

Year	Growth Stages	Explanation	References
2013-2015	Introduction of Building Information Modeling (BIM)	The early 2010s saw the widespread adoption of BIM as a fundamental technology in the construction industry. An integrated approach in construction industries is developed with the help of BIM.	[115-119]
	Emergence of Smart Construction Sites	Construction industries started using IoT. This helped to collect real-time data on the impact of construction activity's environmental conditions, worker safety, and performance of equipment. R&D on smart sensors and wearables laid the foundation for the IoT-driven construction sector.	[120-124]
2015-2020	Rise of the Internet of Things (IoT) and Sensors	The mid-2010s witnessed a surge in the use of IoT devices and sensors for monitoring construction site conditions, equipment health, and worker safety. This ushered in an era of data-driven decision-making and improved project visibility.	[125-127]

	Artificial Intelligence (AI) and Machine Learning (ML) Adoption	Application of AI & ML was increased in the construction sector for planning, predictive analytics, and risk assessment. Due to these technologies, the efficiency of the decision-making process was increased and construction workflow was optimized.	[128, 129]
	Robotics and Automation in Construction	To reduce repetitive and manual tasks, the use of robots and automated machinery was promoted. Project managers started using drones for construction site surveying, monitoring, and inspections. This led to increased construction process efficiency and safety.	[130-133]
	Augmented Reality (AR) and Virtual Reality (VR) Integration	Communication and collaboration between construction project stakeholders are enhanced by using AR and VR technologies. These allowed quick design visualization, reviews, and training.	[134-138]
2020-2022	Cloud Computing for Collaboration	For remotely located construction project teams, cloud computing became a useful tool. This allowed seamless communication and data sharing among teams. Hence, led to an enhancement in project management efficiency.	[139-142]
	Blockchain for Transparency and Security	Blockchain technology was used by construction industries to ensure transparency and security in construction data management, contracts, and transactions. This led to the development of a trustful environment for various construction processes.	[143-145]
	3D Printing Innovations	Construction industries started using 3D printing technology to construct complex building components and even entire buildings. This technology allowed construction industries to adopt sustainable construction practices.	[146-148]
2022 Onward	Digital Twins and Predictive Analytics	Construction industries adopted the digital twin technology which allowed them to simulate and monitor the construction projects in real-time. Also, predictive analytics was used to identify the potential issues and optimize resource allocation.	[149-151]
	Integration of Sustainable Practices	Construction 4.0 increasingly focused on sustainability, with technologies like green building materials, energy-efficient designs, and	[152-154]

		environmentally friendly construction materials and construction methods.	
	Continued Emphasis on Safety	Safety on construction sites is enhanced by using advanced wearable technologies and smart sensors. This led to a reduction in number of incidents and improved worker well-being.	[155-157]
	Further Automation with AI and Robotics	Due to the increasing demand for automation in construction industries, advancements in AI and robotic technology are taking place rapidly. This is helping construction industries to improve process efficiency and reduce manual labor requirements.	[158-160]

4.3 Barriers associated with Adoption of Construction 4.0

Although Construction 4.0 holds significant potential, several challenges impede its full implementation [161-163]. One of the primary barriers is the conservative nature of the construction industry, which has historically been slow to adopt new technologies [164-166]. This resistance stems from a lack of technological awareness, high implementation costs, and fragmented industry structures that hinder the seamless integration of digital solutions [167-169]. A major challenge is the digital skills gap within the workforce [170-172]. Many construction professionals lack the necessary training to work with advanced digital tools such as BIM, IoT, and AI [173-175]. This is exacerbated by the reluctance of older generations to adopt new technologies, further slowing the digital transformation [176, 177]. To address this, ongoing education and upskilling are critical, with industry stakeholders increasingly investing in training programs to overcome these barriers [178, 179]. Financial constraints also present a significant hurdle, particularly for small and medium-sized enterprises (SMEs), which struggle with the high costs associated with technology acquisition and maintenance [180, 181]. Public-private partnerships, along with government support, are essential to mitigating this issue and encouraging widespread adoption of Construction 4.0 technologies [182, 183]. Interoperability between different digital platforms and technologies is another key challenge in Construction 4.0 [184, 185]. The lack of standardized protocols and fragmented systems often results in poor communication and data sharing across the supply chain of construction materials [186-188]. Overcoming this requires the development of unified standards and frameworks that ensure seamless integration and collaboration across different construction phases [189-191]. In terms of overcoming strategies, collaborative ecosystems, partnerships, and the co-creation of digital solutions between stakeholders such as contractors, architects, and software providers have been proposed as effective approaches [192-194]. These partnerships can facilitate knowledge transfer and help align technological innovations with on-site realities [195, 196].

A recent survey revealed that only 15% of construction firms worldwide have fully embraced digital transformation, with the majority citing barriers such as high implementation costs, lack of skilled workforce, resistance to change, and inadequate regulatory frameworks [197-200]. Additionally, the sector faces unique challenges in aligning technological integration with sustainable development goals (SDGs), particularly in addressing resource inefficiency and environmental concerns [201-204]. Additionally, there is limited research on

how to strategically address these barriers to facilitate smoother deployment of Construction 4.0 technologies in the construction industry [205, 206]. Furthermore, the barrier management framework for the adoption of Construction 4.0 technologies in construction industries has not been thoroughly explored [207, 208].

Table 4.3 highlights the barriers to the adoption of Construction 4.0 in the construction industry. These barriers link closely to the United Nations Sustainable Development Goals (SDGs). They affect economic, social, and environmental sustainability. High initial costs (B1), budget constraints (B7), and lack of funding for innovation (B11) impact SDG 9 (Industry, Innovation, and Infrastructure). They slow down the growth of strong infrastructure and inclusive industries. Barriers like lack of compatibility (B2), unreliable new technologies (B4), and technology integration issues (B5) affect SDG 8 (Decent Work and Economic Growth). They reduce productivity and slow economic progress. Limited expertise (B3), insufficient training programs (B18), and high training costs (B22) block SDG 4 (Quality Education). They limit skill development needed for Industry 4.0. Resistance to change (B12), cultural resistance (B26), and fear of job loss (B24) create social gaps. They slow SDG 10 (Reduced Inequalities) by making technology-driven industries unequal. Cybersecurity concerns (B6), lack of standards (B31), and legal uncertainties (B32) challenge SDG 16 (Peace, Justice, and Strong Institutions). Slow decision-making (B15), supply chain complexities (B30), and policy uncertainty (B34) affect SDG 13 (Climate Action) and SDG 7 (Affordable and Clean Energy). Solving these barriers is necessary to drive innovation and achieve sustainable growth.

Table 4.3: Barriers Linked to the Adoption of Construction 4.0

Barrier	Code	Description	Sustainability parameters considering the SDGs	References
High Initial Cost	B1	High costs of adopting and implementing new technologies.	Affects innovation, financial sustainability, and industry infrastructure.	[38-40]
Lack of Compatibility	B2	New technologies are often incompatible with existing systems, leading to operational inefficiencies.	Limits seamless integration, hinders innovation, and disrupts supply chain efficiency.	[63 & 84]
Limited Technical Expertise	B3	Organizations face difficulties due to a lack of experts who understand and can manage new technologies.	Low efficiency, inability to scale technology, and skills gap in the workforce.	[117, 118]
Reliability of New Technologies	B4	Concerns about the reliability and performance of new technologies.	Affects industry trust, innovation growth, and performance consistency.	[55, 56]

Technology Integration Issues	B5	Challenges in integrating new technologies with traditional systems and operations.	Delays in innovation, resource inefficiency, and increased operational costs.	[68 & 74]
Cybersecurity Concerns	B6	Risks associated with data security when implementing new technology solutions.	Impacts innovation by limiting the adoption of advanced technologies due to security concerns.	[103-105]
Budget Constraints	B7	Limited budgets prevent the adoption of costly innovations and new technologies.	Affects financial sustainability, scalability, and technological advancements.	[77, 83 & 100]
Uncertain Return on Investment	B8	Uncertainty in gaining financial returns from technology adoption leads to slow adoption rates.	Economic sustainability and cost-effectiveness reduce risk-taking in innovation.	[14-16]
High Maintenance Costs	B9	Technologies with high maintenance costs discourage long-term use and adoption.	Affects long-term financial viability and resource efficiency in industries.	[19-22]
Lack of Financial Incentives	B10	Government and industry incentives for adopting technology are limited or unavailable.	Limits financial sustainability and innovation in industry practices.	[24, 25]
Lack of Funding for Innovation	B11	Organizations face challenges in securing funds to support innovation.	Affects research and development, limiting new technology breakthroughs.	[33-35]
Resistance to Change	B12	Employees and management often resist change, making it difficult to implement new practices.	Social sustainability and adaptability to change are hindered by cultural resistance.	[42-44]
Poor Change Management	B13	Organizations struggle to manage change effectively, slowing down innovation adoption.	Impacts operational efficiency and organizational adaptability.	[47-49]
Lack of Leadership Support	B14	Leadership reluctance to support technological changes limits innovation within organizations.	Restricts strategic decision-making and innovation-driven initiatives.	[207, 209, 215 & 227]

Slow Decision-Making Processes	B15	Prolonged decision-making processes hinder the swift adoption of new technologies.	Limits operational agility, innovation, and competitive advantage in industries.	[146-151]
Internal Communication Issues	B16	Poor internal communication obstructs the implementation of new processes and technologies.	Operational inefficiencies, low adaptability, and coordination challenges.	[173-176]
Project Management Inefficiencies	B17	Inefficient project management affects the smooth integration of new technologies.	Affects sustainability in resource management and project delivery timelines.	[181, 182]
Insufficient Training Programs	B18	Lack of comprehensive training programs to upskill employees in new technologies.	Hinders skills development and reduces employee efficiency in using advanced technologies.	[186, 187]
Limited Awareness	B19	Employees lack awareness about the benefits of new technologies, resulting in low adoption rates.	Affects the promotion of innovation, scalability, and economic sustainability.	[229, 230]
Lack of Specialized Training	B20	Lack of training institutions offering programs specific to Industry 4.0 and new technologies.	Restricts employee upskilling and innovation in organizational processes.	[223-225]
Employee Reluctance to Learn	B21	Resistance among employees to acquire new skills, makes technology adoption challenging.	Hinders skill development, employee growth, and operational sustainability.	[88-90]
High Training Costs	B22	High costs of providing specialized training limit employee participation in upskilling programs.	Limits accessibility to knowledge and skills crucial for technological advancement.	*Input from construction industry expert*
Traditional Work Practices	B23	Employees are accustomed to traditional methods, resisting the adoption of new technologies.	Limits operational innovation, productivity, and efficiency in the industry.	*Input from construction industry expert*

Fear of Job Loss	B24	Employees fear losing their jobs to automation and advanced technologies.	Impacts organizational morale and cultural sustainability.	*Input from construction industry expert*
Social Reluctance for Acceptance of Technologies	B25	Societal reluctance to accept new technologies hinders large-scale adoption.	Reduces the innovation capacity, limits market expansion, and scalability of new technologies.	*Input from construction industry expert*
Cultural Resistance	B26	Cultural resistance within organizations and society makes change difficult.	Hinders progress toward innovation, limits economic and operational sustainability.	*Input from construction industry expert*
Lack of Demand	B27	Low market demand for innovative technologies makes it difficult to justify investment.	Affects financial sustainability, slows industry growth, and limits competitiveness.	*Input from construction industry expert*
Low Market Maturity	B28	Markets are not mature enough to sustain advanced technologies and innovative products.	Limits the growth of innovation, affecting sustainability in technological adoption.	*Input from construction industry expert*
Lack of Competition	B29	Low competition in the market leads to limited pressure for technological innovation.	Stifles innovation and market dynamism, reducing industry-wide progress.	*Input from construction industry expert*
Supply Chain Complexity	B30	Complex supply chains make it difficult to integrate new technologies smoothly.	Impacts operational efficiency and sustainability in resource management and delivery.	*Input from construction industry expert*
Lack of Standards and Regulations	B31	The absence of clear standards and regulations hampers the adoption of new technologies.	Affects operational efficiency and industry-wide innovation.	*Input from construction industry expert*
Legal Concerns	B32	Legal ambiguities surrounding the use of advanced technologies raise concerns for organizations.	Affects innovation adoption and long-term sustainability in industries.	*Input from construction industry expert*
Liability Issues	B33	Organizations face potential liability concerns when using new technologies,	Hinders innovation, creates financial risks, and limits the	*Input from construction industry expert*

		making adoption slower.	industry's capacity for growth.	
Government Policy Uncertainty	B34	Uncertainty in government policies related to technology adoption makes investment risky.	Slows down technological progress, innovation, and sustainability in industry practices.	*Input from construction industry expert*

4.4 Construction 4.0 Innovation Ecosystem and its Perspectives

The innovation ecosystem for Construction 4.0 is a connected network. It brings together different stakeholders to support digital change in construction [209-211]. As shown in Figure 4.1, the Quadruple Helix Model provides a clear structure. It includes Academia, Industry, Government, and Civil Society. This ensures a balanced approach to technology, policies, skills, and public involvement [212-214]. The model helps in using Construction 4.0 technologies effectively. It improves productivity and cost efficiency. It also supports sustainability in the construction industry [215-217].

Academia helps in developing Construction 4.0 technologies. Universities and research centres focus on new materials, digital fabrication, automation, and AI in construction [218-220]. They work with industry through research projects and innovation hubs. This ensures that new technologies meet industry needs. Universities also train professionals by adding Construction 4.0 topics to courses. This helps workers gain the skills needed for digital construction [221-223].

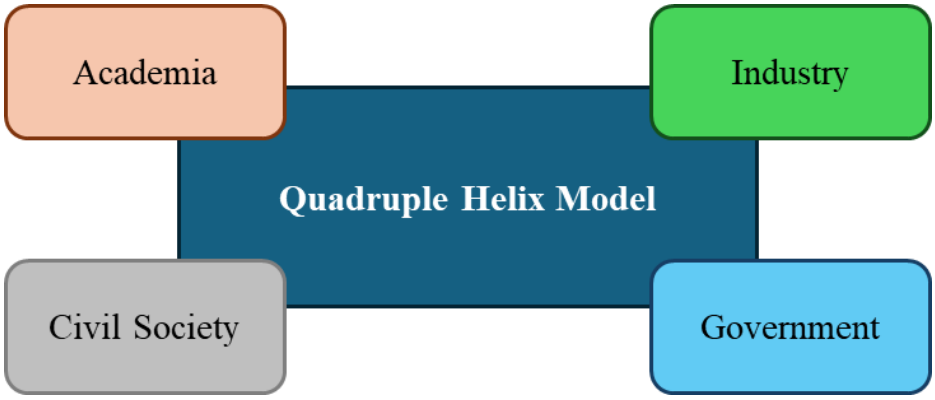


Figure 4.1: Perspectives Adapted from the Quadruple Helix Model of Innovation.

The construction sector includes big companies, SMEs, tech providers, and startups. It plays a key role in digital transformation [224-226]. Firms use automation, robotics, prefabrication, and IoT to boost efficiency and reduce risks. Tech startups create AI tools, blockchain contracts, and real-time site monitoring systems [227-229]. Industry works with academia and government to transfer and adopt new technologies. Companies invest in R&D, venture capital, and public-private partnerships. These efforts help in developing and using smart construction technologies [230-232].

The government helps in adopting Construction 4.0 by making policies, rules, and financial plans. It sets standards for technology, safety, and sustainability [32, 34 & 47]. It ensures new methods are used responsibly. The government gives tax benefits, grants, and funds for digital projects [183 & 191]. It also invests in smart city development. Legal bodies

work with universities and industries to create laws for BIM, smart contracts, and AI-based project approvals. This ensures smooth and legal digital growth in construction [121 & 127].

Civil society includes workers, users, professional groups, and local communities. It plays an important role in using Construction 4.0 technologies [141-145]. As automation and digitalization reshape construction jobs, reskilling programs and workforce adaptation initiatives are essential to minimize disruptions [87, 88]. Industry-wide collaborations with trade unions, labor organizations, and NGOs help in developing inclusive policies for digital workforce transformation [91-93]. Additionally, public engagement is crucial for promoting social acceptance of smart infrastructure projects. By integrating citizen feedback, participatory urban planning, and ethical considerations in AI-based decision-making, the innovation ecosystem ensures that digital transformation aligns with societal needs [167-169].

Several researchers have explored the potential, benefits, and challenges of Construction 4.0; however, limited research has been dedicated to developing a comprehensive innovation ecosystem framework for its adoption [96, 97]. Additionally, most studies on Construction 4.0 innovation ecosystems have primarily focused on developed economies, with minimal attention given to developing countries, where digital transformation in construction is still in its nascent stage [113, 114]. Table 4.4 shows the list of perspectives and their components empowering the Construction 4.0 innovation ecosystem framework. In total, 18 components (05 academia components, 04 industry components, 05 government components, and 04 civil society components) which support the Construction 4.0 ecosystem framework are identified.

Table 4.4: List of Perspectives and their Components

Code	Components	References
Perspective: Academia (Code: P1)		
A1	Availability of R&D facilities in Construction 4.0 technologies such as BIM, digital twin, IoT, AI, and robotics to drive innovation.	[32-34]
A2	Establishment of university-industry collaboration for technology co-development, pilot projects, and real-world implementation of digital solutions.	[43-45]
A3	Inclusion of Construction 4.0 skills in academic curricula to train professionals in smart construction methods, automation, and AI-driven decision-making.	[55, 56]
A4	Development of incubation centers and startup ecosystems to promote entrepreneurship in construction technology and automation.	[66, 67]
A5	Implementation of digital simulation and virtual prototyping tools such as VR/AR-based training modules for enhanced construction planning.	[71, 72]
Perspective: Industry (Code: P2)		
I1	Adoption of smart construction technologies including IoT-enabled site monitoring, AI-powered automation, and blockchain for project management.	[114, 115]
I2	Investment in digital infrastructure such as cloud-based BIM platforms, cybersecurity solutions, and AI-driven project scheduling.	[117, 118]
I3	Expansion of construction technology startups and innovation hubs to accelerate the commercialization of Construction 4.0 solutions.	[121, 122]

I4	Reskilling and upskilling of the construction workforce to enable adaptation to AI-driven automation, robotics, and digital twin applications.	[124, 125]
Perspective: Government (Code: P3)		
G1	Development of national policies and regulatory frameworks to support Construction 4.0 adoption and digital transformation.	[147, 148]
G2	Provision of financial incentives, tax benefits, and subsidies for companies investing in digital construction technologies and automation.	[119 & 141]
G3	Promotion of public-private partnerships (PPPs) to foster collaborative innovation and large-scale infrastructure digitization.	[204 & 214]
G4	Investment in smart city infrastructure to integrate AI-powered, IoT-driven, and digitally connected urban environments.	[64, 65]
G5	Enforcement of green building regulations and carbon-neutral initiatives to promote sustainable construction practices.	[83-86]
Perspective: Civil Society (Code: P4)		
C1	Encouragement of public engagement in smart urban planning to align construction innovations with community needs and environmental concerns.	[94-96]
C2	Addressing of ethical and social implications related to automation, job displacement, and equitable access to Construction 4.0 technologies.	[161, 162]
C3	Conduction of awareness campaigns on the benefits of Construction 4.0 to improve acceptance of digital transformation and smart infrastructure.	[186-188]
C4	Engagement of civil society in policy feedback mechanisms to ensure that construction regulations reflect public concerns and societal needs.	[196-198]

4.5 Researcher's Contribution Analysis

The contribution analysis reveals the distribution of researchers across different research types and subject areas in the field of Construction 4.0. It provides an overview of the types of studies being conducted and the researchers' focus areas, which can be helpful in understanding the research landscape in this domain.

[84], and [93] have presented a case study based on IoT implementation in the construction industry. The purpose of this study is to analyze the behavior in construction businesses due to the implementation of IoT. [71], [89], and [94] have presented a review paper on the paradigm shift of construction industries due to IoT implementation. This research paper has explored the opportunities and barriers linked to IoT implementation in the construction sector. [118], and [127] have designed and developed an autonomous robot to perform the construction activities on site. The study focuses on the evaluation of the performance of autonomous robots and identifies possible future improvements in design. [133], and [177] have presented a case study based on the implementation of 3D printing in the construction industry. This study focuses on exploring the feasibility and cost-effectiveness of using 3D printing technology in the construction industry. [224] reviewed the impact of 3D printing technology on the construction sector. [229] discussed a case study based on AI implementation

in the construction industry. The study aims to explore the importance of AI algorithms in improving construction project management, processes, and safety. [47] reviewed the impact of AI on the construction sector. Also, emerging trends, ethical considerations, and potential applications of AI in the construction sector are explored. [155] presented a case study on the implementation of Cyber-Physical Systems (CPS) in the construction sector. The purpose of this study is to analyze the impact on efficiency and productivity due to the integration of digital technologies into the physical construction process. [124] presented the theoretical framework for the adoption of CPS in the construction industry. Also, the risks associated with the adoption of CPS are explored. [144] presented a case study based on the importance of ML in the construction industry. The study aims to explore the impact of ML algorithms on the predictive maintenance of equipment and the quality of construction activities. [91], and [103] have explored the impact of digital twins on the construction sector. This study has explored the applications and challenges of digital twins in the construction sector. [22] explored the importance of big data analytics in the construction industry through the case study. This study has found that big data analytics enhances the decision-making process, and project planning and management in the construction industry. [73] integrated digital twins and autonomous robots, and performed experimental analysis to identify the impact of integration on construction process efficiency.

4.6 Exploratory Observations from Industry and Academia

To complement the theoretical insights derived from the literature, exploratory visits were conducted to both active construction sites and a leading academic institution. These visits provided a grounded understanding of current challenges, technological practices, and academic innovations in the context of Construction 4.0. The insights gained helped shape the research direction by validating practical gaps and exploring forward-thinking solutions.

4.6.1 Construction Site Visits

Visit 1: Taloja Flyover Bridge Construction (B.G. Shirke Construction Technology Pvt. Ltd.)

The first visit was conducted on 30th March 2024 at a flyover bridge construction site in Taloja, managed by B.G. Shirke Construction Technology Pvt. Ltd. The primary observations included:

- Significant project delays, with a timeline deviation of nearly three years from the original schedule, highlighting concerns related to project management and execution.
- Severe safety violations, including non-use of helmets by workers and absence of systematic safety monitoring, indicating a lack of safety culture.
- Lack of proper material storage and handling that resulted in ineffective utilization of materials, and high chances of wastage and accidents.

These problems in conjunction highlighted the necessity of digitalized solutions to monitor in real-time, enhance safety implemented through such tools as well as integrating project-creation into a streamlined process, which all are core components imagined under the Construction 4.0 Hamiltonian.

Visit 2: Precast Casting Yard, Navi Mumbai (B.G. Shirke)

The second visit was made on 5th April 2024 on to the precast casting yard site of B.G. Shirke located in Navi Mumbai. The trip offered further understanding of semi industrialized building. Notable observations were made as follows:

- Space limitations which restricted casting volume and productivity.
- A shortage of skilled labor, which risked compromising quality and throughput despite the structured nature of precast work.
- Risks associated with steam curing, demanding skilled supervision to ensure temperature and humidity control.
- Multiple safety hazards, such as risks from heavy machinery, manual handling, and hot work activities.

The visit also revealed the untapped potential for digitalization through automated production planning, IoT-enabled monitoring for curing processes, and the use of UAVs for progress tracking. These digital interventions could significantly mitigate operational challenges and improve productivity and safety.

Visit 3: CIDCO Mass Housing Project, Nawade, Navi Mumbai

Also conducted on 5th April 2024, the third visit was to the CIDCO Mass Housing Project at Nawade. This large-scale residential construction site showcased a mix of conventional and semi-mechanized techniques. Observations included:

- 0Compromised construction quality in areas such as concrete finishing and structural integrity.
- Lapses in safety protocols, particularly in lifting operations and site movement.
- Lack of digital project monitoring systems, suggesting low penetration of Construction 4.0 tools like BIM or project management software.
- Inefficient material handling and use of substandard water, raising long-term concerns for durability and quality.

Recommendations from this visit emphasized the urgent need for digital quality assurance systems, IoT-based material tracking, project monitoring software, and training for supervisors and site workers which is again aligning directly with the objectives of Construction 4.0 but found to be significantly lacking in practice.

4.6.2 Academic Observations: Visit to the University of Malaga, Spain

From 26th June to 30th July 2023, a study visit was undertaken at the University of Malaga, Spain, to explore academic initiatives and research activities aligned with Construction 4.0. Unlike the construction site visits which reflected the practical challenges of implementation, this academic exposure offered a forward-looking view of research-driven solutions, innovation ecosystems, and international best practices. Key highlights of the visit are as follows:

- The University of Malaga fosters an integrated approach to Construction 4.0 by encouraging collaboration between the faculties of engineering, architecture, and computer science. This synergy promotes a holistic view of how digital technologies can be embedded across design, planning, and execution phases.

- Demonstrations of BIM, VR environments, and IoT-based applications highlighted the institution's proactive stance on smart construction. These tools were showcased as enablers for real-time decision-making, error reduction, and project optimization.
- The university houses several ongoing research initiatives focused on automation, sustainability, and data-driven construction management. Faculty members and students appeared deeply engaged in generating new knowledge applicable to real-world construction scenarios.
- Close partnerships with construction firms and technology companies were evident through joint research projects and internship programs. These collaborations ensure that academic research is not isolated but contributes meaningfully to industry transformation.
- A culture of continuous learning was visible, with regular workshops and training sessions designed to upskill both students and professionals in emerging digital tools and Construction 4.0 practices.
- The interaction among the students showed a lot of interest and knowledge about sustainability, digital transformation, and the place of education in driving the transformation in industry.
- The focus on green construction, energy-efficient buildings, and smart waste management systems were dominant trends throughout projects and discussions that emphasize the focus of the institution on sustainable development objectives.

Benefits of Construction 4.0 can be achieved through the example of the University of Malaga, emphasizing the importance of interdisciplinary research, connections with the industry, and college students. The trip served as a reminder of the fact that it is not just technological preparedness that will determine whether Construction 4.0 will succeed but also innovation ecosystems and human capital development. The insights gained from this academic environment offer a contrast and complement to the ground realities observed at construction sites and serve as a springboard for identifying research priorities.

The overall impression of the construction industry 4.0, gained through the visits to the industry sites, the academic visit to the University of Malaga, allow having a complete picture of the present and future of Construction 4.0. On one hand, site observations highlighted critical operational inefficiencies, safety violations, lack of digital tools, and skill shortages. On the other hand, the academic experience revealed advanced research, digital tool integration, and innovation ecosystems ready to shape future transformations. This contrast emphasizes a significant disconnect between theoretical advancements and field-level implementation. While academia is rapidly advancing toward intelligent, sustainable, and integrated construction practices, the actual adoption at ground level remains limited and fragmented.

4.7 Research Gaps

- Most of the papers added very restricted contents about current prior studies on Construction 4.0.
- Lack of research on understanding of the holistic landscape of Construction 4.0, and its implementation framework.
- Lack of research on capturing and prioritizing all relevant barriers associated with implementation of Construction 4.0 and barrier management framework is observed.
- Lack of research on construction 4.0 innovation ecosystem framework and causal relationship among its components is observed.

5. RESEARCH METHODOLOGY

In this research work, various electronic databases (such as Science Direct, Google Scholar, Web of Sciences, and SCOPUS) are used to perform a literature review. A set of research papers has been compiled from electronic databases by using several keywords and their combinations i.e. Industry 4.0; Industry 4.0 Technologies; Industry 4.0 and the Construction Industry; Construction 4.0; Construction 4.0 Technologies; Industry 4.0 and Construction 4.0; Barriers and Construction 4.0; and Innovation Ecosystem and Construction 4.0. While the primary focus of this research is on Construction 4.0, the use of broader terms such as "Industry 4.0" and "Industry 4.0 Technologies" was essential due to the foundational role that Industry 4.0 plays in the development of Construction 4.0 technologies. Many of the enabling technologies in Construction 4.0 (such as IoT, Artificial Intelligence, Robotics, and Big Data) originated and were extensively studied in the context of Industry 4.0 before being adapted for use in the construction sector. Thus, incorporating broader terms ensured that we captured a comprehensive set of studies that discuss the evolution, application, and integration of these technologies, even in domains outside of construction. This approach allowed us to understand the technological advancements in Industry 4.0 that have subsequently been applied to Construction 4.0 and to identify trends and gaps that might not have been evident if only narrower, construction-specific terms were used. Various inclusion and exclusion criteria are defined such as; (1) Papers using Construction 4.0 as a method to address issues related to the study area and with conclusions entirely devoted to Construction 4.0 are taken into consideration, and (2) Papers in which Construction 4.0 was only used in catchphrases and not supported by any significant evidence are excluded. Figure 5.1 and 5.2 shows the research methodology flow diagram for research work and hypotheses conceptual framework, respectively. This research work is carried out in following phases:

Phase I:

- A detailed literature review is carried out to understand the concepts, technologies, and evolution of Industry 4.0 and its application in the construction sector.
- Based on the literature review and input from industry experts, the research gaps are identified which help in framing clear research questions and objectives.

Phase II:

- Hypotheses are developed to explore the relationships among various enablers, barriers, risk factors, and drivers of Construction 4.0.
- Specific literature is reviewed to identify and classify the critical components necessary for implementing Construction 4.0.

- Structured data collection methods are employed. This includes interviews with industry experts, questionnaire-based surveys, and field observations to gather empirical evidence.

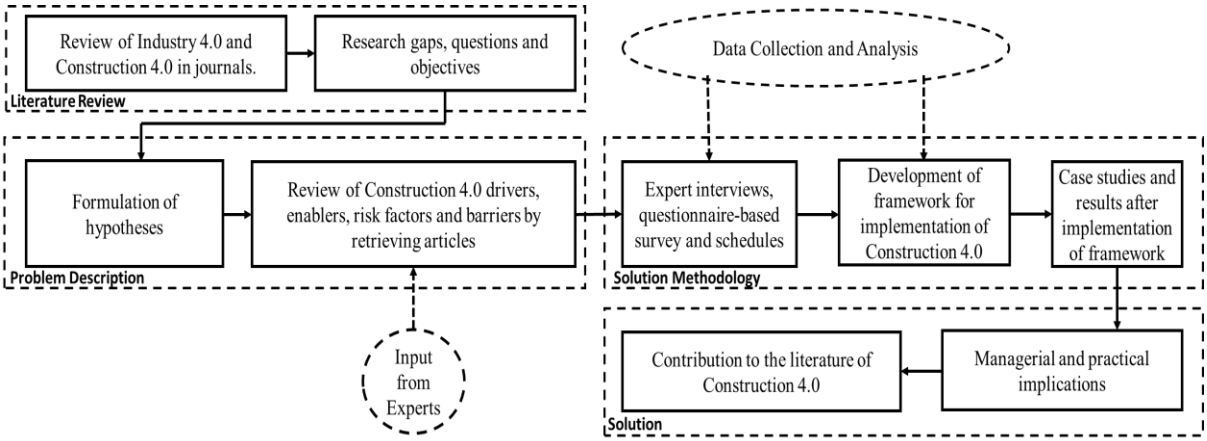

Review of Industry 4.0 and Construction 4.0 in journals.
Research gaps, questions and objectives
Literature Review
Data Collection and Analysis
Formulation of hypotheses
Review of Construction 4.0 drivers, enablers, risk factors and barriers by retrieving articles
Problem Description
Expert interviews, questionnaire-based survey and schedules
Development of framework for implementation of Construction 4.0
Case studies and results after implementation of framework
Solution Methodology
Input from Experts
Contribution to the literature of Construction 4.0
Managerial and practical implications
Solution

Figure 5.1: Research Methodology Flow Chart.

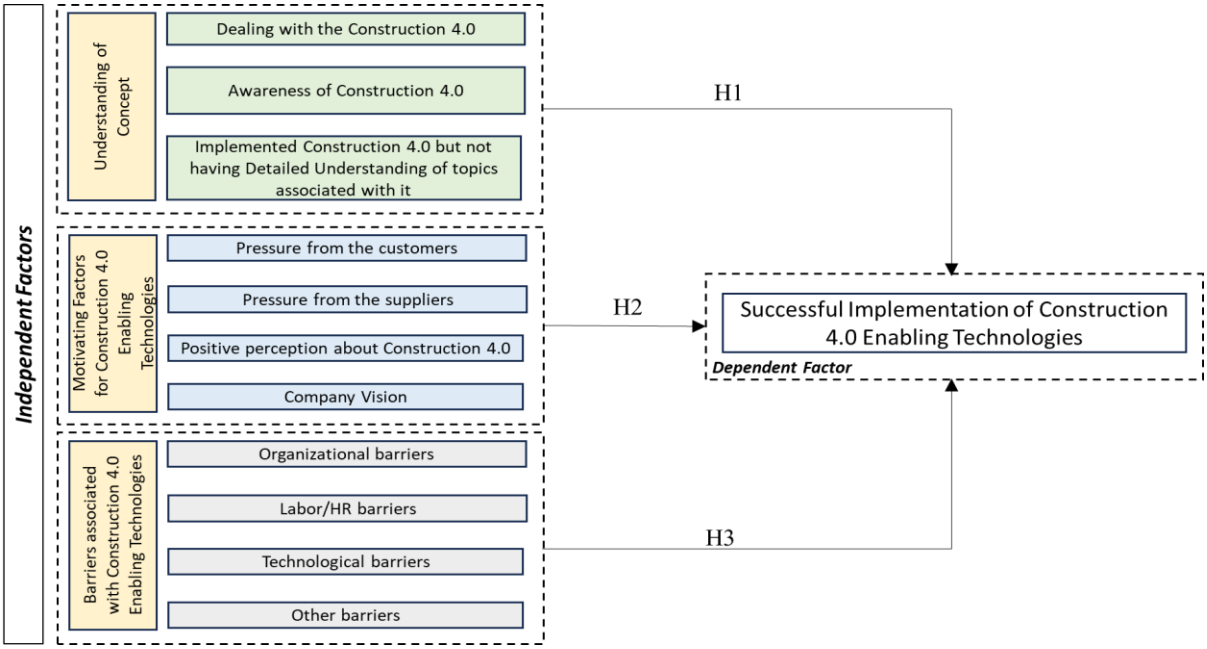


Figure 5.2: Hypotheses Conceptual Framework.

Phase III:

- Based on the analysis from previous phases, a robust and practical implementation framework is developed to integrate Construction 4.0 technologies in real-world projects.
- Case study is conducted in construction industry to test the developed framework.

Phase IV:

- The research adds new insights and perspectives to the academic domain of Construction 4.0.
- The findings are translated into actionable strategies for practitioners, policymakers, and construction managers, enabling informed decision-making and effective implementation.

6. CONTRIBUTIONS

6.1 Determination of Current Adoption Scenario of Construction 4.0 Enabling Technologies *(addressing RO1)*

To determine the current adoption scenario of Construction 4.0, the questionnaires were developed with the assistance of five specialists, two of whom were from educational institutions of higher education and three of whom were from the industrial sector. In addition to having an understanding of Construction 4.0, these experts have at least ten years of experience working in their respective fields individually. The identification of these specialists was carried out by examining the information that was accessible on official websites, LinkedIn, and Google Scholar profiles. During the preliminary testing of the questionnaire, there were a total of ten participants: five professionals from the construction industry and five academics. There were questions posed to these experts, and they were questioned if there were any questions that they did not understand, as well as whether there were any unclear questions. Their recommendations were taken into consideration while modifying some things. Cronbach's alpha (α) was used to determine the reliability of the survey instrument. The result obtained from the test was 0.72, which indicates that the instrument had internal consistency. It is important to investigate the understanding of the Construction 4.0 concept, the implementation scenario of Construction 4.0 enabling technologies in construction industries, the factors that motivate the implementation of Construction 4.0, and the impact that Construction 4.0 enabling technologies have on construction processes. To achieve this, the construction industries of all sizes (i.e. large, medium, and small) were investigated to gather data via the application of questionnaires and interviews with industry professionals.

The questionnaire-based survey included 43 industries. Out of the 43 industries, 09 were industrial construction industries, 05 were commercial construction industries, 11 were residential construction industries, 06 were institutional construction industries, and 12 were civil construction industries. The questionnaire-based survey was completed by three respondents from each industry. Consequently, 129 respondents participated in the questionnaire-based survey. To evaluate the implementation scenario of Construction 4.0 enabling technologies in their business, 43 industries receive physical visits. During the visit, the authority of the participating industry was provided with the printed questionnaire forms, and all members of the industry submitted responses, resulting in a 100% response rate. The questionnaires were divided into four sections. These sections encompassed inquiries regarding the application of Construction 4.0 enabling technologies, understanding of Construction 4.0, the factors that motivate the implementation of Construction 4.0, and the influence of Construction 4.0 enabling technologies on construction processes. Expert interviews were conducted to determine the understanding of Construction 4.0 by construction industries, the technologies that enable Construction 4.0 in their business, the barriers that the construction industry has faced during the implementation of the Construction 4.0 concept, and the impacts of Construction 4.0 on sustainability pillars. 10 experts were participated in expert interview process.

6.1.1 Understanding of the Construction 4.0 Concept in Construction Industries

Figure 6.1 highlights a notable recognition of the Construction 4.0 concept among the sectors examined. All responders have unanimously reported that they have been actively

involved in Construction 4.0 for more than three years. This indicates a general recognition of the phrase among professionals in the construction industry. Nevertheless, the data also indicates a deficiency in comprehension, as a significant proportion (63%) of organizations admit to being acquainted with the phrase but lack a thorough knowledge of its extent and consequences. Furthermore, 50% of the industries polled (consisting of 31% strongly agreeing and 19% agreeing) acknowledge being aware of Construction 4.0 but have not yet started implementing it in practice. This is a critical phase in the adoption process when people are aware of the principles related to Construction 4.0, but they are hesitant or resistant to putting them into practice. However, despite the differences in understanding and application, the overall conclusion derived from the data is positive i.e. the construction industry has a strong degree of knowledge of Construction 4.0. This indicates a promising opportunity for future investigation, learning, and incorporation of cutting-edge technologies and processes encompassed within the Construction 4.0 framework. With sufficient advice and assistance, these industries are ready to take advantage of the revolutionary capabilities of Construction 4.0, leading to increased efficiency, creativity, and sustainability in the construction sector. Although there are still hurdles, the data encourages to continue efforts to bridge the gap between knowledge and action in the field of Construction 4.0.

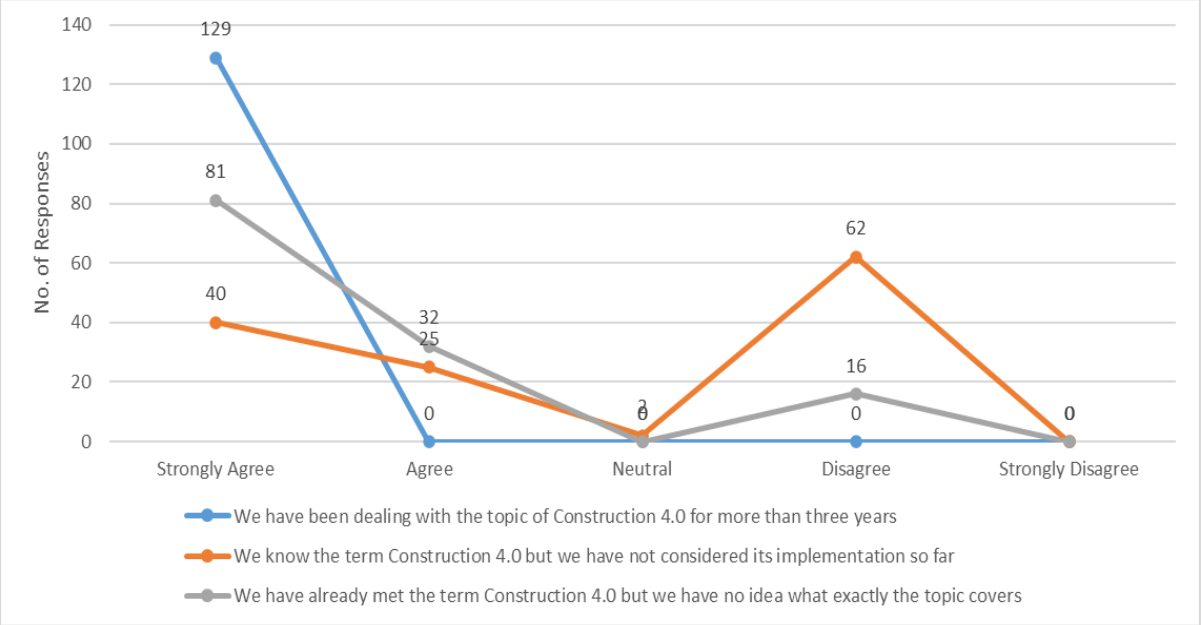


Figure 6.1: Understanding of Construction 4.0.

6.1.2 Spread of Construction 4.0 Enabling Technologies

In this research work, various Construction 4.0 enabling technologies such as the Internet of Things (IoT), Artificial Intelligence (AI) and Machine Learning (ML), Autonomous Robots, Augmented Reality (AR), 3D Printing, Cloud Computing, Cybersecurity, Simulation, Drones, Big Data Analytics, Smart Sensors, Building Information Modeling (BIM) and Digital Twin are considered. In the questionnaire, the second question was "Which Construction 4.0 enabling technologies are used in your industry?". The information provided in Figure 6.2 provides significant insights into the implementation and usage of several Construction 4.0 enabling technologies in the sectors that were surveyed. Out of all the technologies mentioned,

Building Information Modeling (BIM) is the most commonly used and holds the highest position have earned first rank. The popularity of BIM underscores its crucial role in facilitating collaboration, visualization, and decision-making throughout the whole project lifecycle, leading to increased efficiency and decreased mistakes. The study reveals that the Internet of Things (IoT) is widely adopted in the construction industry, ranking second, due to its role in enhancing connectivity, data gathering, and automation. Drones, which are increasingly used for site monitoring and surveying, have earned the third rank, contributing to improved productivity and safety. Smart Sensors and Simulation are important for predicting outcomes and monitoring construction in real-time, making building processes more efficient. Autonomous Robots are also on the rise, helping automate tasks and improve efficiency on job sites. 3D Printing, AI and Machine Learning, Augmented Reality, and Digital Twin technology are being used but not as widely yet, indicating there's still a lot of potential to explore in these areas for design and construction. On the other hand, Cloud Computing, Cybersecurity, and Big Data Analytics, all ranked eleventh, are underutilized, pointing to potential challenges in integrating these technologies into the construction industry. The rankings offer useful insights into the present state of Construction 4.0 technologies, showcasing sectors with high acceptance rates and significant chances for future innovation and implementation in the construction industry.

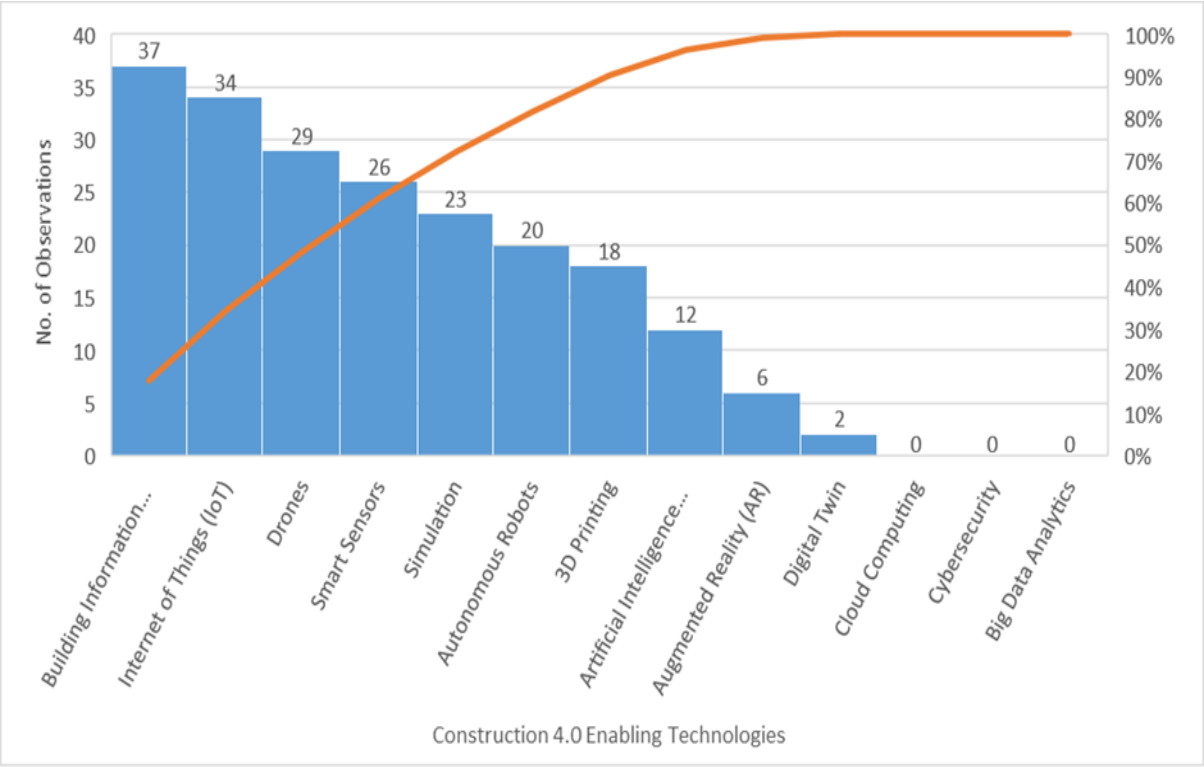


Figure 6.2: Spread of Construction 4.0 Enabling Technologies.

6.1.3 Motivating Factors for Construction 4.0 Implementation

Figure 6.3 shows the key factors that drive the use of Construction 4.0 technologies in the different sectors. Firstly, a significant proportion of respondents (68%) credit the motivation for adopting Construction 4.0 principles to the pressure exerted by their consumers. This indicates an increasing need from customers for building procedures and results that are

more effective, technologically sophisticated, and environmentally friendly. Customer expectations are exerting a growing influence on business practices, prompting organizations to embrace creative strategies to fulfill changing needs and maintain competitiveness in the market. However, a significant majority of industries (88%) attribute the use of Construction 4.0 enabling technology to their management vision. This emphasizes the proactive role of executives in acknowledging the strategic significance of adopting digital transformation and innovation inside their organizations. Management vision involves a proactive strategy that prioritizes the long-term advantages of using cutting-edge technology to improve productivity, quality, and operational efficiency. Furthermore, it emphasizes the acknowledgment of Construction 4.0 as a catalyst for promoting organizational growth, adaptability, and market dominance in a swiftly changing industrial environment. These findings highlight the complex reasons why Construction 4.0 practices are adopted. External pressures from customers and internal strategic vision from management both contribute to driving technological innovation and organizational change in the construction sector. This dual viewpoint is a comprehensive approach to embracing digital transformation, where the requirements of customers and the dynamics of the market interact with strategic foresight and organizational leadership to create a plan for sustainable development and competitive advantage.

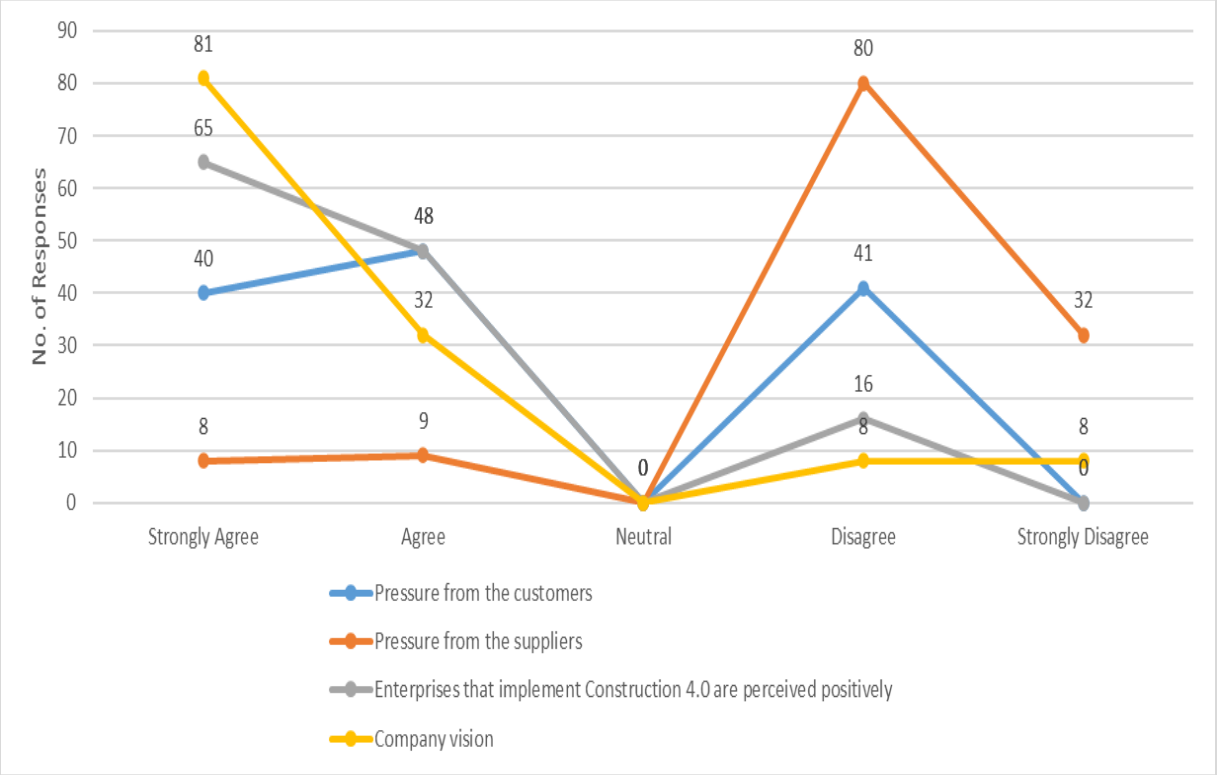


Figure 6.3: Motivating Factors for Construction 4.0 Implementation.

6.1.4 Impact of Construction 4.0 Enabling Technologies on Construction Processes

Table 6.1 provides a thorough understanding of the perceived impacts of Construction 4.0 enabling technologies on several elements of the construction sector. These findings offer useful insights into the profound impact of using digital technology and creative practices in construction companies. Effective coordination among stakeholders (such as architects, engineers, and project managers) ensures streamlined workflows and reduces redundancies in

the digital construction process. Collaboration, facilitated through cloud-based BIM platforms, enhances real-time data sharing and improves decision-making efficiency. However, challenges such as fragmented project teams and data security concerns can hinder seamless BIM integration. Addressing these barriers requires structured communication protocols, standardized BIM guidelines, and investment in collaborative tools to enhance interoperability across platforms. Figures 6.4, 6.5, and 6.6 emphasize the diverse effects of Construction 4.0 technologies on many facets of the construction sector, including process efficiency, economic performance, environmental sustainability, and worker dynamics. Construction organizations may tap into new development possibilities, enhance competitiveness, and build resilience by adopting digital transformation and innovation. This approach also allows them to effectively tackle important issues and meet social demands in the built environment. Nevertheless, it is crucial for individuals and organizations involved in the sector to work together, allocate resources toward the growth of skilled workforce, and embrace a comprehensive strategy for integrating technology. This will ensure that the advantages of Construction 4.0 are distributed fairly and in a manner that supports long-term sustainability throughout the construction ecosystem.

Table 6.1: Impact of Construction 4.0 Enabling Technologies

Impact	Findings
Improved Process Efficiency and Effectiveness	Most industries (81%) agree that Construction 4.0 technologies enhance process efficiency and effectiveness, streamlining operations and improving communication and collaboration.
Enhanced Inventory and Warehouse Management	Nearly all respondents (94%) see a significant improvement in inventory and warehouse management due to Construction 4.0, which optimizes inventory levels and logistics, leading to cost savings.
Improved Supply Chain	Almost all respondents (94%) believe Construction 4.0 greatly impacts supply chain management by optimizing procurement, transportation, and supplier relationships, improving transparency, and reducing risks.
Overall Economic Benefit	All respondents (100%) highlight the overall economic benefits of Construction 4.0, including increased productivity, competitiveness, and profitability, contributing to economic growth in the industry.
Efficient Use of Energy	The overwhelming consensus (94%) emphasizes Construction 4.0's role in improving energy efficiency, reducing carbon footprints, and promoting environmental sustainability through smart technologies.
Efficient Monitoring of Air Pollution Index	A majority (63%) support the use of Construction 4.0 technologies for monitoring air pollution, with room for improvement in using sensors and data analytics to better manage environmental impact and comply with regulations.
Re-use of Material	Recognition (75%) of Construction 4.0's role in material reuse shows a growing focus on reducing waste and promoting sustainability through advanced recycling and modular building methods.
Scrap Reduction	A large majority (81%) agree that Construction 4.0 technologies effectively reduce waste and enhance construction processes through digital fabrication and automated systems.

Safer Workplace	Unanimous agreement (100%) on the role of Construction 4.0 technologies in improving workplace safety through sensors, wearable devices, and real-time monitoring, fostering a strong safety culture.
Increased Employees' Morale	Most people (94%) believe Construction 4.0 improves employee morale by enhancing job satisfaction, engagement, and career growth opportunities, supported by training and development programs.
Job Loss Fear	Some employees worry about job loss due to new technology. Companies should address these concerns by being transparent, offering training, and demonstrating that technology supports rather than replaces jobs.
Special Skills Requirement	A significant portion (69%) acknowledges the need for specialized skills to use Construction 4.0 technologies effectively. Ongoing training and development are essential for improving technical skills and adaptability.

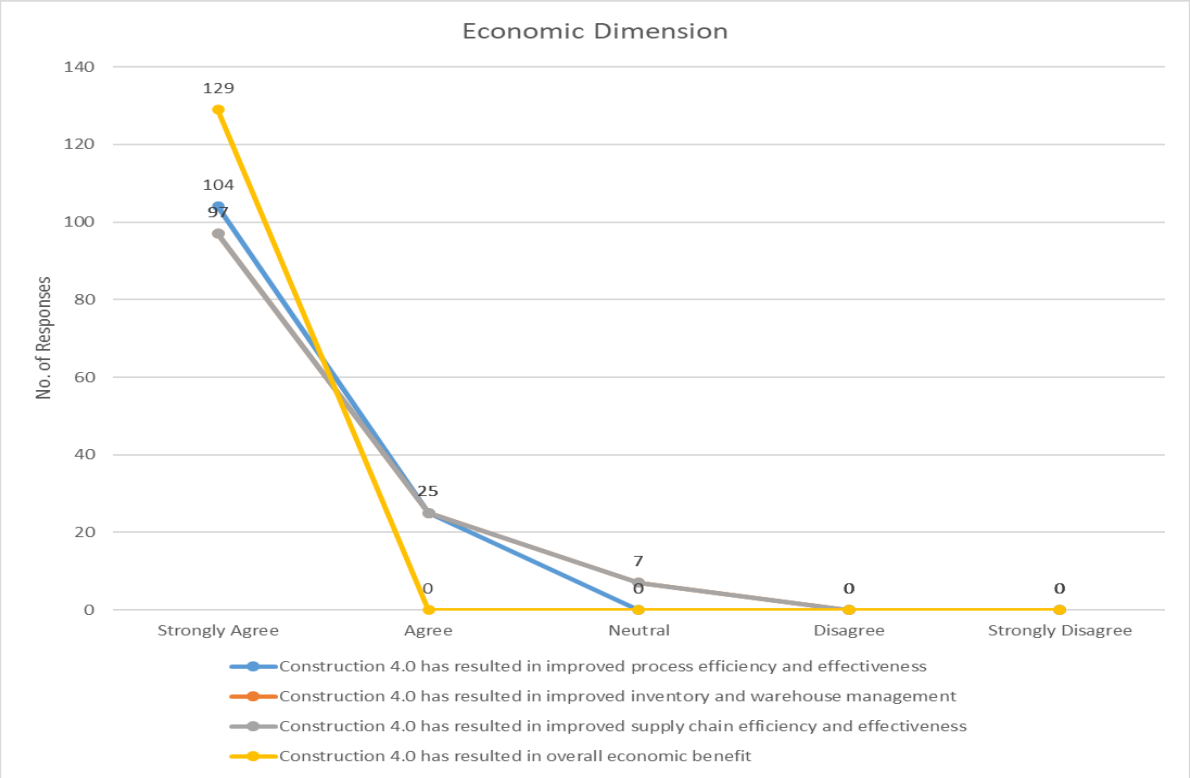


Figure 6.4: Impact of Construction 4.0 Enabling Technologies - Economic Dimension.

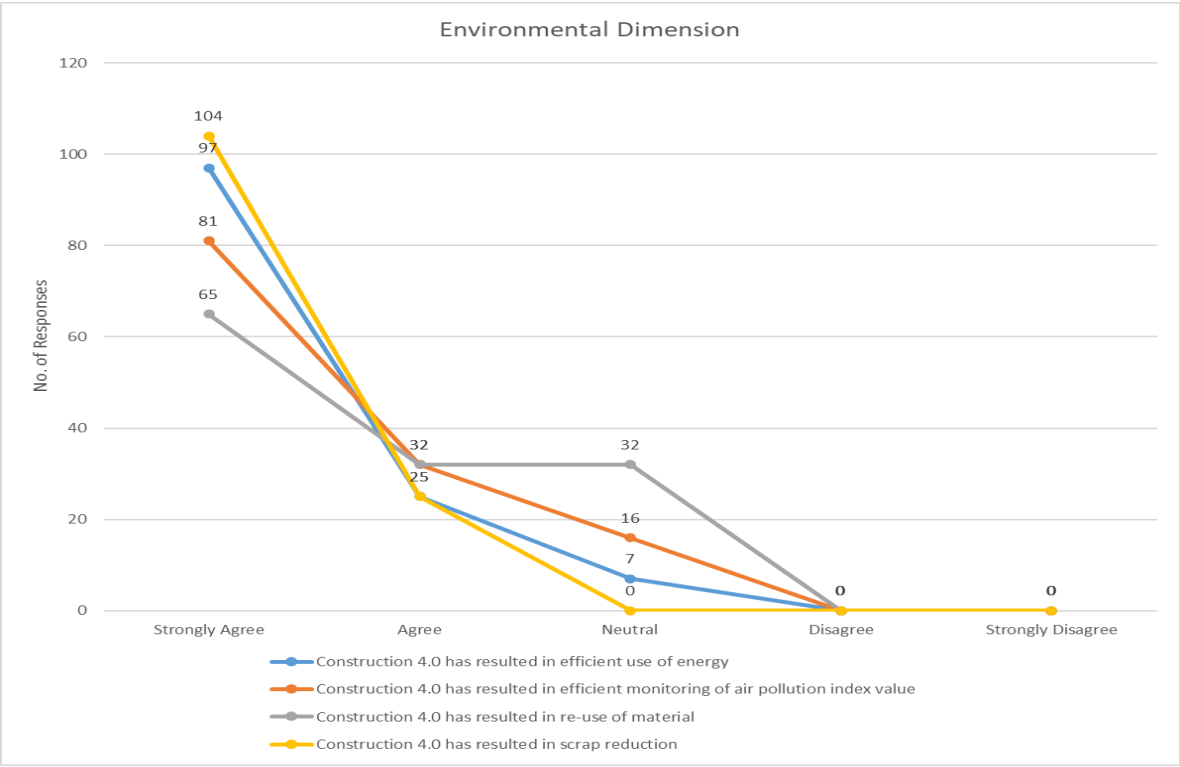


Figure 6.5: Impact of Construction 4.0 Enabling Technologies - Environmental Dimension.

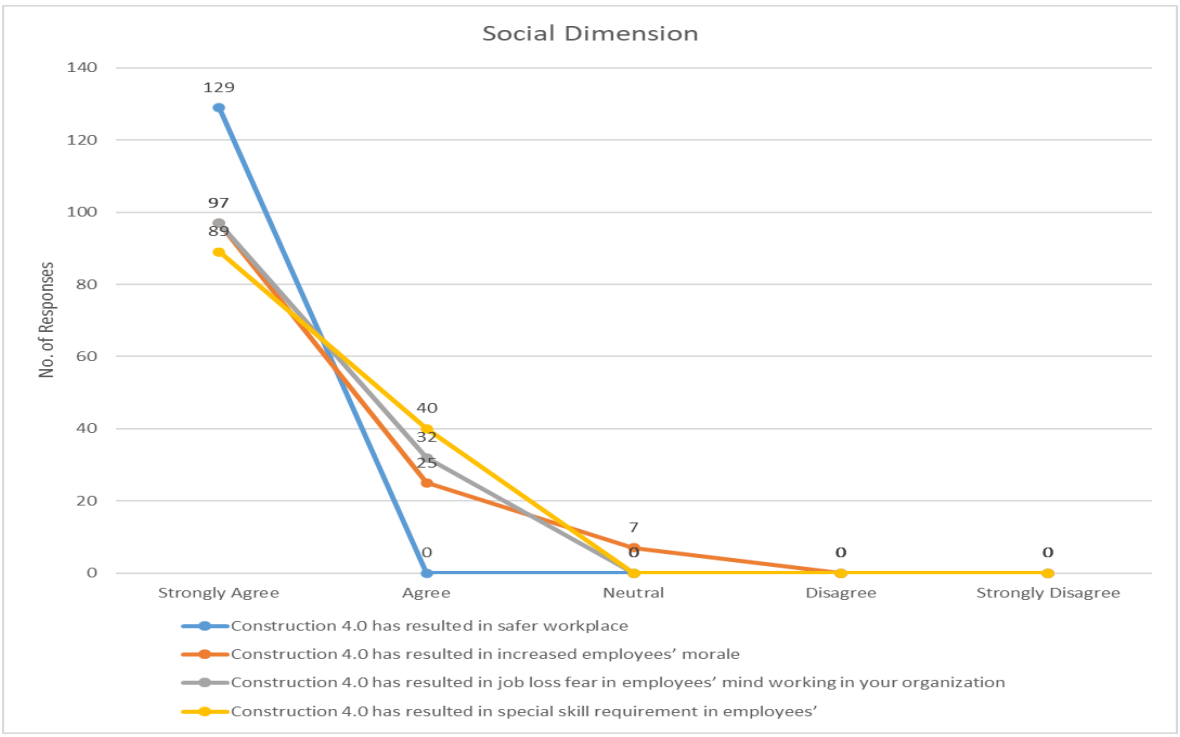


Figure 6.6: Impact of Construction 4.0 Enabling Technologies - Social Dimension.

6.1.5 Outcomes of Expert Interview

Construction 4.0 represents a revolutionary shift in the construction industry, driven by advanced technologies that enhance information sharing, predictive analytics, and the creation of smart, interconnected systems. This transformation is expected to boost industry

productivity by 20-30%, primarily through faster decision-making, with data exchange technologies reducing decision times by 50%. The transition to Construction 4.0 is bringing about significant changes, but it's not without its challenges. One of the biggest issues is managing the workforce. The shift to automation and digitization has resulted in a 15% reduction in blue-collar jobs, and another 20% of workers need reskilling to stay relevant. This skill gap is worsened by the difficulty in hiring workers skilled in digital technologies, leading to a 25% increase in the time needed to find qualified candidates. Resistance to these new technologies is also a major concern, with 30% of workers hesitant to adopt them, which hurts productivity and drives labor costs up by 10-25%. Additionally, the cost of training and reskilling adds 15% to operational expenses, further highlighting the financial strain of this transition. The absence of a standardized framework for implementing Construction 4.0 complicates matters even more, extending project timelines by 20% and increasing employees' fears of job loss, with 40% worried about their job security due to automation.

To overcome these challenges, there's a need for policy reforms, especially in education, to produce the skilled workforce necessary for this digital transformation. Without these reforms, the industry could face a 10-15% slowdown in growth. Vocational training is crucial and could increase the availability of skilled labor by 25%, helping to close the skill gap and reduce the 10-15% rise in HR costs linked to managing a workforce that needs to adapt to new technologies. Implementing more flexible work policies could also help retain talent, potentially reducing turnover rates by 15%. However, the lack of standard practices and the resulting rigidity in processes may hinder project adaptability by 10%, making the role of consultants and specialized suppliers more important, even though this reliance could raise project costs by 10-15%.

In this new environment, the core skills required have shifted dramatically. About 80-90% of new roles now require expertise in information technologies and technical skills. Communication, problem-solving, and innovation have become more critical than ever, boosting team collaboration by 25%, reducing project errors by 20%, and increasing efficiency by 30%. Analytical skills are now essential, improving decision accuracy by 35%, while cognitive flexibility and emotional intelligence are crucial for managing the complexities of a rapidly evolving industry. These skills are vital for leaders who must guide their teams through this digital transformation, improving productivity by 15% and reducing team conflicts by 20%.

The impact of Construction 4.0 technologies on construction processes is significant. Digital tools have sped up project delivery times by 20%. Site monitoring through cameras and sensors has reduced on-site incidents by 30%, while predictive maintenance, enabled by sensor data, has decreased equipment downtime by 40% and cut maintenance costs by 20-25%. Safety compliance has improved by 35% with the use of wearable technology, which also boosts worker productivity by 15%. Real-time tracking and resource allocation tools have further optimized project efficiency, reducing resource allocation errors by 25% and improving utilization rates by 20%. Digital collaboration tools, like cloud-based software and mobile apps, have streamlined communication, cutting project delays by 15-20% and significantly improving the speed and accuracy of project management.

Despite these advancements, the workforce is facing significant changes. The fear of job loss due to automation affects 40% of workers, leading to resistance against new

technologies. This resistance requires more training efforts, which adds 10-15% to operational costs. Continuous learning and skill development have become essential, with 50% of the workforce needing ongoing training to stay relevant in a digital industry. This shift has also led to organizational restructuring, with automation reducing the need for traditional managerial roles by 10-15% and creating new leadership positions focused on digital strategy. The demand for creativity and strong analytical skills is now higher than ever, fostering innovation that enables faster problem-solving and more efficient project execution.

Finally, the environmental impact of Construction 4.0 is highly positive. The adoption of smart technologies has reduced material waste by 25%, resulting in 15-20% savings on raw materials. Energy efficiency has improved by 20% thanks to precision monitoring tools that optimize energy use. The integration of material recycling and scrap reduction technologies has further reduced raw material costs by 15% and disposal costs by 25%, while conserving natural resources by 20%. This not only makes construction projects more sustainable but also contributes to long-term cost savings and environmental preservation. Overall, while Construction 4.0 presents significant challenges, the benefits in terms of productivity, efficiency, and environmental sustainability are substantial, making it a critical evolution for the construction industry.

6.1.6 Validation of Hypotheses

Table 6.2 shows the P-value and decision. The results of the hypothesis testing for the moderating effect of specific variables on the relationship between key factors and the adoption level of Construction 4.0 enabling technologies are examined. Two main hypotheses were tested, each focusing on different aspects of the implementation of Construction 4.0.

Table 6.2: P-value and Decision

Independent Factor	Dependent Factor	P-value	Decision
Understanding of Concept	Adoption Level of Construction 4.0 Enabling Technologies	1.37E-18	Reject null hypothesis
Motivating factors for Construction 4.0 implementation		1.49E-18	Reject null hypothesis

The p-value for the hypothesis test is 1.37E-18, which is significantly lower than the commonly accepted significance level of 0.05. This result strongly suggests that the moderating variables “Dealing with Construction 4.0, Awareness of Construction 4.0, and Implemented Construction 4.0 but not having Detailed Understanding of topics associated with it” significantly impact the relationship between "Understanding of Concept" and “Adoption Level of Construction 4.0 Enabling Technologies.” As a result, we reject the null hypothesis and accept the alternative hypothesis, confirming the significant moderating effect of these variables. The p-value for this test is 1.49E-18, which is also significantly lower than 0.05. This result indicates that the moderating variables “Pressure from the Customers, Pressure from the Suppliers, Enterprises that implement Construction 4.0 are perceived positively, and Company vision” have a significant impact on the relationship between "Motivating factors for Construction 4.0 implementation" and “Adoption Level of Construction 4.0 Enabling Technologies.” Consequently, the null hypothesis is rejected in favor of the alternative

hypothesis, confirming the significant moderating effect of these variables. Both tests provided strong evidence that the moderating variables significantly influence the relationship between the independent variables (Understanding of Concept and Motivating Factors) and the dependent variable (Adoption Level of Construction 4.0 Enabling Technologies). The extremely low p-values in both cases led to the rejection of the null hypotheses, affirming the importance of these moderating variables in the adoption process of Construction 4.0 technologies.

6.1.7 Reasons for Low Adoption of Construction 4.0 Enabling Technologies

The reasons for the low adoption of construction 4.0 enabling technologies are shown in Figure 6.7. The adoption of Construction 4.0 enabling technologies, which include advancements like Building Information Modeling (BIM), Internet of Things (IoT), robotics, and artificial intelligence (AI), has been notably slow across the construction industry. This concept can be linked to a wide range of factors that include different areas like the market, technology, economics, organization, regulations, culture, and education as well. From a technological viewpoint, one of the primary barriers is the high initial cost associated with the implementation of advanced construction 4.0 enabling technologies. For firms or small-scale industries, the initial investment required for hardware, software, and installation and implementation can be significant. Additionally, many existing components and systems used in construction projects may not be compatible with new technologies, necessitating costly renovations and alterations. Another important and genuine issue is the lack of technical expertise within the man power. As these technologies are relatively new, there is a shortage of professionals and experts who possess the requisite skills to effectively implement and manage the technological problems. This skill gap makes it challenging for construction industries to fully control the potential of Construction 4.0 for the betterment of society. For small and medium-sized enterprises (SMEs) the constraints of budget play a significant role economically. They particularly may struggle to allocate funds for technological investments. The uncertainty surrounding the return on investment (ROI) is another critical and crucial factor. The benefits of these technologies often manifest over the long term even the lack of immediate financial returns on the investment can frighten construction industries and companies from adopting technological innovations. Additionally, the way many construction companies are organized can make it harder to adopt new methods. There is often a reluctance to change, particularly in an industry that has long depended on manual processes and labor-intensive techniques. This resistance is sometimes compounded by a lack of support from top management, who may not fully appreciate the strategic value of these technologies. Poor change management, inadequate planning, and improper execution can further worsen these challenges, as these challenges can lead to unsuccessful implementations with disaster results.

Regulatory and legal factors also play a vital role in the slow adoption of Construction 4.0 technologies. The construction industry often lacks clear standards and regulations for the implementation of these technologies, creating a level of uncertainty, insecurity, rules, guidelines, and risk that industries may be unwilling to take on. Additionally, there are potential legal issues related to data security, privacy, and intellectual property that can pose significant challenges. The market itself may not be fully prepared for these advancements. There can be a lack of awareness and lack of demand from clients for high-tech solutions. The maturity level of the market also affects adoption; in regions where the construction industry is not yet fully developed, the urge for implementation of advanced technologies is often very low. In the

construction industry, both cultural and social factors play significant roles in shaping practices and attitudes. Understanding and addressing both cultural and social factors is essential for driving progress in this traditionally slow-to-evolve industry. The construction industry is known for its strong attachment to traditional methods and approaches, which makes it prone to resistant to change. There is often a fear among workers that the successful trial of automation and robotics could lead to the loosening of their jobs. The fear of loss of a job creates a disturbance in the level of acceptance of technology and ultimately adoption process lowers at the ground level. Finally, educational training programs can significantly impact the rate of the adoption of construction 4.0 enabling technologies into construction projects. There is a notable lack of training, Awareness programs and educational programs specifically focusing on Construction 4.0 enabling technologies. This leads to a lack of awareness and understanding of how beneficial these technologies can be, which in turn slows down their adoption even more. In summary, the slow adoption of Construction 4.0 technologies is a multifaceted issue influenced by overrunning costs, technical challenges, economic constraints, organizational inactivity, regulatory uncertainties, market immaturity, cultural resistance, and a lack of educational training initiatives. To tackle these challenges, a good strategy is necessary. This involves investing in training and skill development, gaining strong leadership support, clarifying regulations, and changing the industry's culture to embrace new ideas and innovations gracefully. To facilitate practical adoption of Construction 4.0 technologies, the research study recommends the following strategies: (1) investment in digital skill development, as data indicates a direct correlation between workforce training and BIM adoption success; (2) implementation of standardized protocols, as seen in case studies where regulatory compliance enhanced project efficiency by 20–30%; (3) fostering cross-disciplinary collaboration through integrated project delivery models, which have been shown to reduce cost overruns by up to 15%. These insights provide a structured roadmap for industry practitioners, ensuring measurable improvements in technology adoption and operational efficiency.

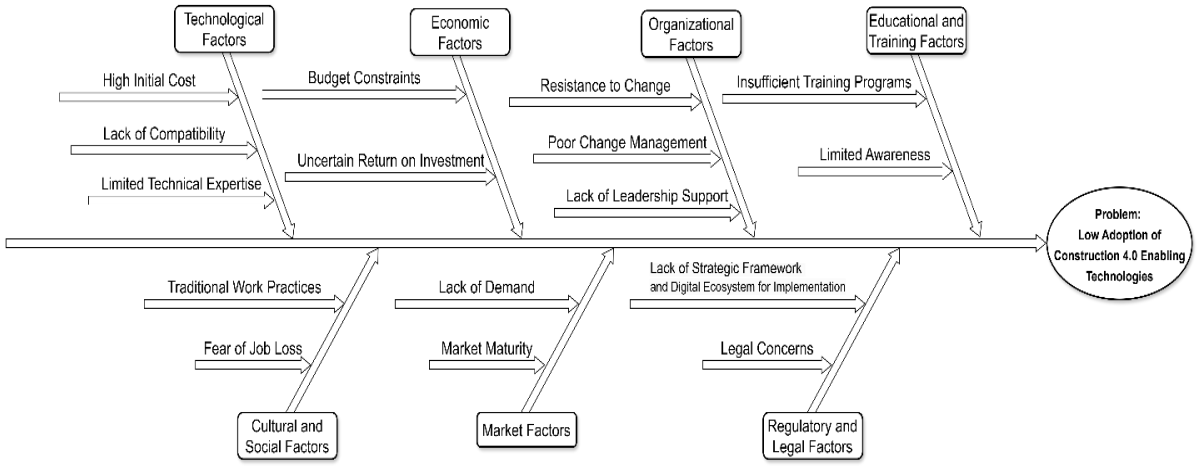


Figure 6.7: Reasons for Low Adoption of Construction 4.0 Enabling Technologies.

6.1.8 Strategic Framework for Construction 4.0 Implementation

The framework for implementing Construction 4.0 in the construction industry (shown in Figure 6.8) is a holistic approach that integrates the use of advanced technologies, change in organizational structure, and continuous improvement to increase efficiency, productivity, and sustainability. The framework begins with strategic planning and setting the vision where the

organization defines its objectives and goals for adopting Construction 4.0 technologies. These goals align with its overall business strategy, assess its readiness for digital transformation, and engage stakeholders to ensure support. This phase sets the foundation for a successful transition by creating a clear roadmap and involving key stakeholders in the process.

Define Objectives and Goals
(Identify the specific objectives of adopting Construction 4.0 e.g., improving project efficiency, reducing costs, enhancing safety)
Assess Organizational Readiness
(Conduct a readiness assessment to evaluate the current state of technology, processes, and workforce capabilities)
Stakeholder Engagement
(Involve key stakeholders i.e. management, employees, clients, suppliers early in the planning process)
Step 1: Strategic Planning and Vision Setting
Client and Supplier Engagement
(Work closely with clients and suppliers to ensure alignment and integration of Construction 4.0 technologies across the value chain)
Build Strategic Partnerships
(Collaborate with technology providers, academic institutions, and industry bodies to stay at the forefront of technological advancements)
Step 8: Collaboration and Ecosystem Development
Identify Relevant Technologies
(Select technologies aligned with the organization's goals, such as BIM, IoT, AI, robotics, drones, and augmented reality (AR))
Develop a Technology Roadmap
(Create a phased roadmap for technology implementation, starting with pilot projects)
Invest in Infrastructure
(Upgrade IT infrastructure to support digital tools, data analytics, and cloud computing)
Step 2: Technology Selection and Integration
Future-Proofing
(Future-proof the organization by staying informed about emerging technologies and trends)
Benchmarking and Best Practices
(Benchmark against industry best practices and adopt lessons from other sectors that have successfully implemented Industry 4.0)
Feedback and Iteration
(Continuously gather feedback from stakeholders and use it to improve processes and technologies)
Step 7: Continuous Improvement and Innovation
Leadership and Governance
(Establish a governance structure to oversee the Construction 4.0 initiative, including leadership roles and responsibilities)
Process Reengineering
(Redesign existing processes to incorporate new technologies, focusing on improving efficiency and reducing waste)
Risk Management
(Identify potential risks associated with technology adoption, such as resistance to change or technical failures)
Step 3: Organizational Change Management
Performance Monitoring and Reporting
(Develop key performance indicators (KPIs) to monitor the impact of Construction 4.0 technologies)
Leverage Data Analytics
(Use data analytics to gain insights into project performance, identify trends, and make informed decisions)
Data Strategy Development
(Establish a data management strategy that defines data collection, storage, and analysis protocols)
Step 6: Data Management and Analytics
Training and Skill Development
(Invest in training programs to upskill the workforce in new technologies and digital tools)
Cultural Transformation
(Foster a culture of innovation and collaboration, encouraging employees to embrace new ways of working)
Change Communication
(Develop a comprehensive communication plan to keep all stakeholders informed about the progress and benefits of the Construction 4.0 initiative)
Step 4: Workforce Development and Culture Change
Scaling Up
(Gradually roll out Construction 4.0 technologies across all projects, ensuring lessons learned are applied)
Evaluate and Optimize
(Assess the outcomes of pilot projects, identifying successes and areas for improvement)
Pilot Testing
(Begin with pilot projects to test the implementation of selected technologies in a controlled environment)
Step 5: Pilot Projects and Scaling

Figure 6.8: Strategic Framework for Construction 4.0 Implementation.

Next is the selection and integration of technology, where the organization identifies the relevant technologies, such as BIM, IoT, AI, robotics, and augmented reality (AR), that align with its strategic goals. A technology roadmap is developed to plan the phased implementation of these technologies, starting with pilot projects to test and refine their application. It is essential to invest in necessary IT infrastructure and ensure interoperability between new and existing systems is crucial at this stage. Equally important are strong cybersecurity measures to protect data and systems from potential threats.

The key part of the framework is Organizational change management, emphasizing the importance of leadership, governance, and process redesign. It's crucial to set up a governance structure to manage the Construction 4.0 initiative and ensure strong commitment from top

management to drive the transformation. Additionally, managing risks effectively is important which includes identifying potential problems and creating strategies to address the problems to give sustainable solutions. Using New technologies, altering existing processes, and adopting digital construction methods can greatly enhance efficiency which reduces waste production.

For the success of Construction 4.0 implementation workforce development and culture change are fundamental. This involves investing in training programs to upskill the workforce in new technologies and digital tools, fostering a culture of innovation and collaboration, and addressing concerns about job security by highlighting the value of new skills and roles. Clear and effective communication is key to keeping all stakeholders informed about the progress and benefits of the digital initiative and incorporating feedback into the strategy.

The scaling phase involves testing the implementation of selected technologies through pilot projects. This process includes gathering data, and refining processes based on the insights gained. Successful pilot projects can then be scaled across the organization, ensuring that lessons learned are applied to optimize technology integration leading to improvement.

Data management and analytics play a significant role in the framework. Developing a robust data strategy that defines data collection, storage, and analysis protocols is essential for leveraging data analytics to gain insights into project performance, identify trends, and make informed decisions. Implementing predictive analytics can help anticipate project risks and optimize resource allocation, while performance monitoring and reporting tools provide real-time insights into project performance.

To keep the momentum going with Construction 4.0, it's crucial to focus on continuous improvement and innovation. This means regularly collecting feedback, comparing your practices with industry standards, and encouraging a culture of trying new things. It's also important to make sure that Construction 4.0 efforts align with sustainability goals, like cutting down on carbon emissions and waste. This approach helps future-proof the organization and ensures it remains competitive. Finally, collaboration and ecosystem development involve building strategic partnerships with the Government, academic institutions, and industry bodies to stay at the lead of technological advancements. Engaging clients and suppliers to ensure alignment and integration of Construction 4.0 technologies across the value chain and educating clients on the benefits of these technologies are vital for fostering a collaborative ecosystem.

❖ ***Implementation of Proposed Framework***

The construction industry is often plagued by safety challenges, inefficiencies, and low compliance with safety measures. At United Builders, Panvel, these issues have contributed to injuries, delays, and reduced worker confidence, highlighting the need for innovative solutions. The emergence of Construction 4.0 technologies offers significant opportunities to address these challenges through advanced, integrated systems. A smart wearable system comprising head and hand protection units was implemented at United Builders, Panvel. The system utilized sensors to monitor gas levels, temperature, and motion, providing real-time alerts and location tracking. Data were collected over a month (December) to analyse safety compliance, emergency response, and worker satisfaction. Comparative analysis was performed using historical data from the past three years. The implementation of the smart wearable system

resulted in reduction in minor injuries, down from an average of five to one during the study period. PPE compliance rates improved significantly, rising to 95%. Emergency response times decreased from an average of 16.33 minutes to 05 minutes. Project delays due to safety issues were reduced from 17.67% to 5%, and worker satisfaction improved to 85%, indicating enhanced confidence in workplace safety measures. The smart wearable system demonstrated its potential to revolutionize construction safety by leveraging Construction 4.0 technologies. It effectively addressed safety concerns, enhanced compliance, and improved operational efficiency. These results highlight the importance of adopting Construction 4.0 technologies for fostering safer, more productive construction environments. Further research is recommended to explore scalability and long-term impacts across diverse construction settings.

6.2 Analysis of Barriers associated with the Adoption of Construction 4.0 *(addressing RO2)*

A separate sheet containing the list of the barriers related to the adoption of Construction 4.0 technologies in the construction sector was presented to the 05 experts (02 from higher education institutions and 03 from the construction sector) for finalizing the barriers. These specialists know Construction 4.0 technologies and possess a minimum of 10 years of professional experience. Subsequently, the TOPSIS technique is employed to rank the identified barriers. Construction sector experts have taken part in a questionnaire-based survey using the TOPSIS approach. The random sampling approach is adopted. The reliability of the survey instrument was tested using Cronbach's alpha (α) and the value obtained is 0.78 indicating an internal consistency. Questionnaires were emailed to 43 construction sector experts, and 41 responses were obtained, resulting in a response rate of 95.34%. It is important to note that the adoption of Construction 4.0 is still in its early stages, with a relatively limited number of industries actively implementing these technologies. Given this context, identifying experts with direct experience in Construction 4.0 remains a challenge. The experts who contributed to this research were discovered by visiting the construction industry. These specialists know Construction 4.0 technologies and possess a minimum of a decade of professional experience in the construction industry. The TOPSIS approach utilizes a scale ranging from 1 to 5. On the scale, 1 represents no impact, 2 represents moderate impact, 3 represents medium impact, 4 represents significant impact, and 5 represents very high impact. Table 6.3 displays the TOPSIS-based ranking of barriers to Construction 4.0 deployment in the construction industry. According to the TOPSIS analysis, the barrier High Initial Cost (B1) and Internal Communication Issues (B16) emerged as the top-ranked barrier, indicating its critical importance in the context of the adoption of Construction 4.0 technologies in the construction industry. This is followed by Project Management Inefficiencies (B17), Lack of Funding for Innovation (B11), Lack of Demand (B27), Technology Integration Issues (B5), Cybersecurity Concerns (B6), and High Maintenance Costs (B9) which constitute the top five barriers demanding attention from stakeholders due to their substantial impact on successful implementation of Construction 4.0. Furthermore, the rankings provided insight into the interplay of various barriers, revealing instances where multiple barriers shared the same rank. For example, barriers B1 and B16 are collectively ranked first, suggesting similar levels of significance. Similarly, barriers B5, B6, and B9 share the fifth position, barriers B2, B8, and B24 share the twelfth position, barriers B3 and B18 share the fifteenth position, barriers B10 and B20 share the twenty-first position, and barriers B22 and B26 share the twenty-second

position. This shows their similar impact on adopting Construction 4.0 technologies. The rankings highlight the connections between different barriers. Many barriers share the same rank up to the twenty-sixth position. This grouping of barriers shows their complex nature. It reflects the many challenges in adopting Construction 4.0 in the industry. To overcome these barriers, stakeholders must focus on high-impact ones. Key barriers include High Initial Cost (B1), Internal Communication Issues (B16), and Project Management Inefficiencies (B17). Other major barriers are Lack of Funding for Innovation (B11), Lack of Demand (B27), and Technology Integration Issues (B5). Cybersecurity Concerns (B6) and High Maintenance Costs (B9) also create challenges. By addressing these barriers, the construction industry can improve adoption. This will help in making construction more efficient and innovative.

Table 6.3: Ranking of Barriers

Rank	Code	Barrier	Rank	Code	Barrier
1	B1	High Initial Cost	**14**	B32	Legal Concerns
	B16	Internal Communication Issues	**15**	B3	Limited Technical Expertise
2	B17	Project Management Inefficiencies		B18	Insufficient Training Programs
3	B11	Lack of Funding for Innovation	**16**	B23	Traditional Work Practices
4	B27	Lack of Demand	**17**	B30	Supply Chain Complexity
5	B5	Technology Integration Issues	**18**	B13	Poor Change Management
	B6	Cybersecurity Concerns	**19**	B4	Reliability of New Technologies
	B9	High Maintenance Costs	**20**	B34	Government Policy Uncertainty
6	B25	Social Reluctance for Acceptance of Technologies	**21**	B10	Lack of Financial Incentives
7	B29	Lack of Competition		B20	Lack of Specialized Training
8	B12	Resistance to Change	**22**	B22	High Training Costs
9	B33	Liability Issues		B26	Cultural Resistance
10	B28	Low Market Maturity	**23**	B19	Limited Awareness
11	B14	Lack of Leadership Support	**24**	B7	Budget Constraints
12	B2	Lack of Compatibility	**25**	B21	Employee Reluctance to Learn
	B8	Uncertain Return on Investment	**26**	B15	Slow Decision-Making Processes
	B24	Fear of Job Loss			
13	B31	Lack of Standards and Regulations			

6.2.1 Strategies to Address the Identified Barriers

Table 6.4 shows that the adoption of Construction 4.0 technologies requires a strategic approach to overcome the identified barriers while aligning with Sustainable Development Goals (SDGs). These strategies are developed by consulting experts who participated in a

structured questionnaire survey, ensuring their relevance and practicality. The proposed strategies include implementing financial support mechanisms to mitigate high costs and funding limitations, enhancing technical training programs to bridge skill gaps and improve workforce readiness, and strengthening cybersecurity measures to safeguard digital systems. Promoting leadership and change management drives organizational commitment while developing standardized policies and regulations ensures compliance and streamlined processes. Raising awareness and market demand educates stakeholders and fosters technological adoption, simplifying technology integration to address compatibility challenges, and encouraging cultural and social acceptance mitigates resistance to change. Each strategy is mapped to specific barriers and SDGs, ensuring a holistic approach that supports economic, social, and environmental sustainability. The 5W2H framework further provides actionable insights, offering clear guidance on what to do, why it is essential, where and when to implement, who is responsible, how to execute, and the associated costs, making these strategies both effective and practical.

Table 6.4: Proposed Strategies to Mitigate the Barriers

Strategy	Mapping with Barriers	Mapping with Sustainable Goals (SDGs)	What	Why	Where	When	Who	How	How Much
Implement Financial Support Mechanisms	B1, B7, B8, B9, B10, B11	1, 8, 9	Provide financial incentives, subsidies, and funding opportunities.	To reduce financial barriers and promote adoption.	Construction companies and technology providers.	During project planning and execution phases.	Government bodies, financial institutions, and industry leaders.	Through tax incentives, grants, and low-interest loans.	Dependent on project scale and industry needs.
Enhance Technical Training Programs	B3, B18, B19, B20, B21, B22	4, 8, 9	Develop specialized training programs for employees.	To address skill gaps and improve technical expertise.	At training centers or on-site facilities.	Before and during technology deployment.	Training institutions and HR departments.	Workshops, certifications, and on-the-job training.	Training costs are based on program duration and scope.
Strengthen Cybersecurity Measures	B6, B4, B5, B32, B33	9, 12, 16	Implement robust cybersecurity frameworks.	To ensure data protection and system reliability.	Across all digital platforms and systems.	Throughout technology implementation and operation.	IT departments and cybersecurity experts.	Using advanced security software and regular audits.	Varies with system complexity.
Promote Leadership and Change Management	B12, B13, B14, B15	8, 9, 17	Foster leadership and effective change management practices.	To overcome resistance and drive adoption.	Within organizational hierarchies.	From planning to implementation stages.	Senior management and change agents.	Leadership training and structured change frameworks.	Costs linked to training and consultancy.

Develop Standardized Policies and Regulations	B31, B32, B34	9, 12, 16	Establish clear guidelines and standards.	To ensure compliance and streamline adoption.	National and industry levels.	Before widespread implementation.	Regulatory bodies and policymakers.	Drafting policies with stakeholder input.	Dependent on administrative requirements.
Improve Awareness and Market Demand	B19, B27, B28, B29	8, 9, 12	Conduct awareness campaigns and market research.	To educate stakeholders and boost demand.	Across industry events and media channels.	Continuously, with focus during early adoption.	Marketing teams and industry associations.	Webinars, trade shows, and online content.	Budget based on campaign scale.
Simplify Technology Integration	B2, B5, B16, B17	9, 12	Adopt modular and compatible technology solutions.	To address integration challenges.	On construction sites and digital systems.	During planning and implementation.	Technology providers and IT teams.	Using APIs and interoperable platforms.	Integration costs are based on existing infrastructure.
Encourage Cultural and Social Acceptance	B23, B24, B25, B26	4, 8, 10	Promote cultural and social benefits of technology.	To reduce resistance and encourage adoption.	At all organizational levels and communities.	Before and during technology introduction.	HR teams and community leaders.	Workshops, town halls, and awareness programs.	Dependent on outreach scope.

6.2.2 Effectiveness of Proposed Strategies

The effectiveness of the proposed strategies has been evaluated by the index shown below:

$$E = \sum (A_i * \text{Log } B_i)$$

Where, E = Effectiveness of proposed strategies
i = Number of strategies… (i = 1 to 8)
A_i = Weight assigned to strategies
R = Strategy rank
B_i = Inverse rank

Five-point Likert scale is used to assign effectiveness scores to each strategy. Where 1 shows Very Low Effectiveness, 2 shows Low Effectiveness, 3 shows Moderate Effectiveness, 4 shows High Effectiveness, and 5 shows Very High Effectiveness. The effectiveness questionnaires were completed by the same experts who contributed to the TOPSIS method, ensuring consistency and reliability in the evaluation process. A uniform weight (Ai = 1) was applied to all strategies, indicating that each strategy was equally prioritized or valued for this calculation. Table 6.5 evaluates the effectiveness of eight proposed strategies using a systematic approach, resulting in an effectiveness index of 4.6, which falls between "high effectiveness" and "very high effectiveness." This calculation combines mean scores, ranks, inverse ranks, logarithmic transformations, and uniform weights to assess each strategy's contribution to the overall impact. For example, "Promote Leadership and Change Management" was the most effective strategy. It had the highest weighted score. In contrast, "Strengthen Cybersecurity Measures" had the lowest impact. This shows areas that need improvement. Evaluating these strategies helps decision-makers use resources wisely.

Table 6.5: Effectiveness Index of Proposed Strategies

S.N.	Strategies	Mean	Rank (R)	Inverse Rank (Bi)	Log Bi	Weight (Ai)	Ai*Log Bi
1	Implement Financial Support Mechanisms	4.24	4	5	0.69	1	0.69
2	Enhance Technical Training Programs	4.27	3	6	0.78	1	0.78
3	Strengthen Cybersecurity Measures	2.71	8	1	0	1	0
4	Promote Leadership and Change Management	4.61	1	8	0.9	1	0.9
5	Develop Standardized Policies and Regulations	3.44	6	3	0.48	1	0.48
6	Improve Awareness and Market Demand	4.39	2	7	0.85	1	0.85
7	Simplify Technology Integration	3.39	7	2	0.3	1	0.3
8	Encourage Cultural and Social Acceptance	3.85	5	4	0.6	1	0.6
Total of Effectiveness Index							**4.6**

6.2.3 Hypothesis Validation

A one-sample t-test was conducted for each barrier using a significance level of 0.05. The test compared the expert ratings, measured on a 5-point Likert scale, against a neutral midpoint of 3. Out of the 34 barriers analyzed, 33 barriers were found to be statistically significant ($p < 0.05$), indicating that experts perceive these barriers as critical to the adoption of Construction 4.0. The remaining 01 barrier were not statistically significant. Refer Table 6.6 for summary.

Table 6.6: Summary of P-value

Barrier Name	Mean	Std Dev	n	t-Statistic	p-value	Result
B1	1.46	0.504854	41	-19.4887	5.00069E-22	Significant
B2	3.44	0.549945	41	5.111657	8.2897E-06	Significant
B3	3.51	0.506061	41	6.480741	9.97778E-08	Significant
B4	4.37	0.487652	41	17.93435	9.95447E-21	Significant
B5	2.17	0.771441	41	-6.8831	2.72907E-08	Significant
B6	2.56	0.593666	41	-4.7352	2.74206E-05	Significant
B7	4.49	0.637258	41	14.94936	5.73125E-18	Significant
B8	3.44	0.549945	41	5.111657	8.2897E-06	Significant
B9	2.39	0.586432	41	-6.6578	5.63501E-08	Significant
B10	4.44	0.634381	41	14.5248	1.52311E-17	Significant
B11	2.17	0.667175	41	-7.9588	8.99082E-10	Significant
B12	2.78	0.570622	41	-2.46321	0.018169615	Significant
B13	4.27	0.448575	41	18.10408	7.11073E-21	Significant
B14	3.22	0.419058	41	3.354102	0.001751899	Significant
B15	4.93	0.263652	41	46.79556	1.50565E-36	Significant
B16	1.49	0.506061	41	-19.1336	9.73267E-22	Significant
B17	2.27	0.448575	41	-10.4447	5.4261E-13	Significant
B18	3.61	0.493865	41	7.905694	1.06156E-09	Significant
B19	4.49	0.506061	41	18.82501	1.75041E-21	Significant
B20	4.41	0.498779	41	18.1605	6.36177E-21	Significant
B21	4.73	0.448575	41	24.71903	7.59393E-26	Significant
B22	4.49	0.506061	41	18.82501	1.75041E-21	Significant
B23	3.63	0.58121	41	6.98632	1.95954E-08	Significant
B24	3.37	0.58121	41	4.030569	0.000242493	Significant
B25	2.41	0.669911	41	-5.59503	1.7517E-06	Significant
B26	4.41	0.498779	41	18.1605	6.36177E-21	Significant
B27	2.24	0.699303	41	-6.92316	2.39964E-08	Significant
B28	2.90	0.663509	41	-0.9415	0.352099143	Not Significant
B29	2.32	0.819726	41	-5.33454	4.05582E-06	Significant
B30	3.73	0.633419	41	7.396705	5.28758E-09	Significant
B31	3.51	0.553261	41	5.927853	5.97005E-07	Significant
B32	3.56	0.708829	41	5.067505	9.54595E-06	Significant
B33	2.59	0.740797	41	-3.58391	0.000909255	Significant
B34	4.41	0.631491	41	14.34396	2.32349E-17	Significant

6.2.4 Barrier Management Framework

Figure 6.9 presents a framework for managing barriers to adopting Construction 4.0 technologies. This framework helps to identify, group, and reduce challenges in a structured way. It divides 34 barriers into six main types: financial, technological, organizational, human resource, market, and supply chain and legal barriers. For financial barriers, solutions include financial incentives, strong ROI models, and funding partnerships. These help to overcome high costs and budget issues. Technological barriers are managed through compatibility improvements, pilot testing, and cybersecurity measures. These steps ensure smooth integration and system security. Organizational barriers include resistance to change and weak decision-making. These are addressed through strong leadership, structured change management, and better internal communication. Human resource barriers are handled with training programs, employee engagement, and cultural change. These efforts help reduce resistance and improve skills. Market barriers arise from low demand and market immaturity. They are tackled through awareness programs, innovation support, and competition growth using case studies. Supply chain and legal barriers are reduced by improving processes, setting clear legal rules, and working with governments to minimize policy uncertainty. The framework ensures continuous improvement through key performance indicators (KPIs). These include ROI, system reliability, change adoption rate, and supply chain efficiency. By aligning solutions with challenges, the framework supports a smooth transition to Construction 4.0. It promotes innovation, operational efficiency, and industry-wide progress.

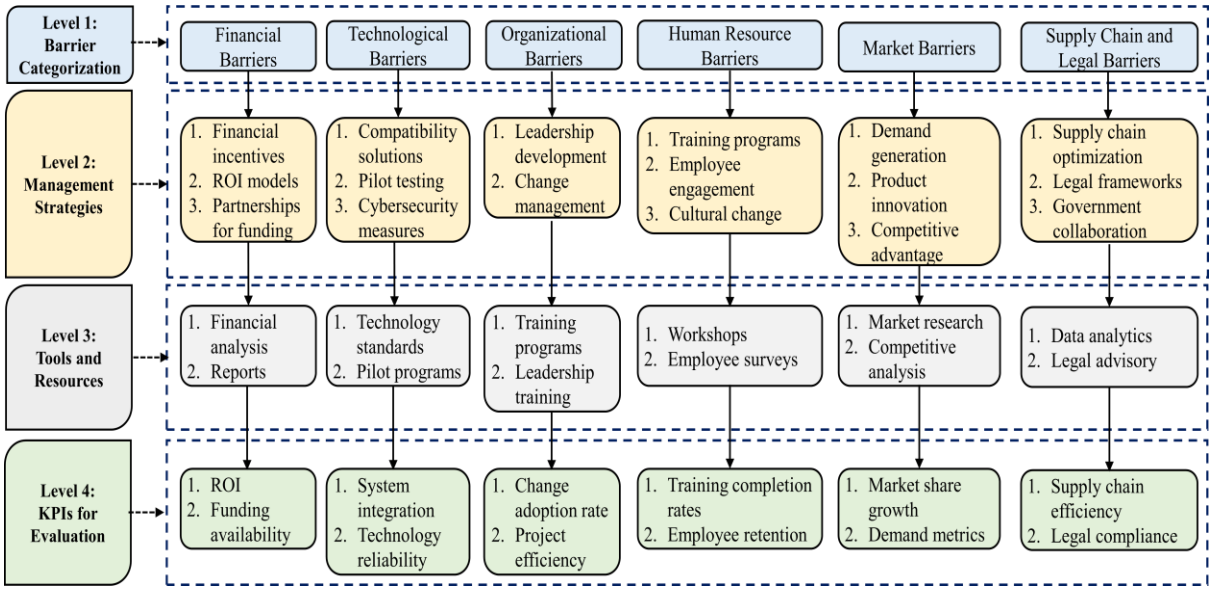


Figure 6.9: Barrier Management Framework.

6.3 Analysis of Perspectives and Components of Construction 4.0 Innovation Ecosystem Framework *(addressing RO3)*

An initial list of perspectives and components for the Construction 4.0 innovation ecosystem framework was compiled through a comprehensive literature review. Subsequently, the identified elements were discussed with five experts (two from higher education institutions and three from the construction industry) who possess expertise in Construction 4.0 and have a minimum of 10 years of professional experience. DEMATEL method was utilized to evaluate the significance of these perspectives and components while identifying causal relationships among them. ISM and DEMATEL are commonly applied for analyzing causal connections and structuring system frameworks, with DEMATEL often being preferred over ISM due to its ability to distinguish relationships with notable variations. Moreover, DEMATEL requires limited data to generate meaningful insights, making it the preferred approach for this study. DEMATEL is designed to examine complex problem groups. This technique employs a scale from 0 to 4, where '0' signifies no influence, '1' represents low influence, '2' indicates moderate influence, '3' denotes high influence, and '4' signifies very high influence. The DEMATEL methodology involves five essential steps: (a) collecting expert opinions and computing the average matrix, (b) deriving the stabilized primary direct-relation matrix, (c) developing the aggregate relation matrix, (d) calculating the sum of rows and columns within the matrix, and (e) establishing the threshold value. Responses for the matrix developed under the DEMATEL method were provided by 12 experts, including three from academia, three from the construction sector, three from the government's industrial policy development sector, and three from civil society. These experts possess knowledge of Construction 4.0 and have a minimum of 10 years of professional experience. They were identified through information available on official websites, LinkedIn, and Google Scholar accounts. After collecting responses from these 12 experts, the DEMATEL analytical technique was applied to examine significant perspectives and components.

The significance of perspectives within the Construction 4.0 innovation ecosystem framework is determined using the (Ri + Ci) values. As shown in Table 6.7, the (Ri + Ci) values for Academia (P1), Industry (P2), Government (P3), and Civil Society (P4) are 12.73, 13.19, 12.45, and 12.26, respectively. A higher (Ri + Ci) value indicates a more critical evaluation perspective, while a lower value signifies a less significant one. Based on this criterion, the ranking of the four perspectives is P2 > P1 > P3 > P4. As shown in Table 6.7, values exceeding the threshold value (α) are represented as Aij, indicating the interaction between perspectives. For instance, since A21 (=1.80) is greater than α (=1.58), an arrow in the cause-and-effect diagram is directed from P2 to P1. Figure 6.10 illustrates the cause-and-effect relationships among the four perspectives of the Construction 4.0 innovation ecosystem framework. The analysis reveals that Academia (P1) and Industry (P2) exhibit mutual interactions.

Table 6.7: T-Matrix Calculation

Perspective	P1	P2	P3	P4	Ri	Ci	Ri+Ci	Ri-Ci	Threshold Value
P1	1.43	**1.67**	**1.65**	**1.81**	6.56	6.17	12.73	0.39	1.58
P2	**1.80**	1.53	**1.80**	**1.96**	7.08	6.10	13.19	0.98	
P3	1.55	1.57	1.37	**1.75**	6.24	6.21	12.45	0.02	
P4	1.39	1.34	1.39	1.31	5.43	6.83	12.26	-1.40	

Based on the (Ri – Ci) values, the four perspectives are categorized into two groups: cause and effect. Perspectives with positive (Ri – Ci) values are assigned to the cause group, while those with negative (Ri – Ci) values belong to the effect group. In this study, Academia (P1), Industry (P2), and Government (P3) are classified under the cause group, whereas Civil Society (P4) falls under the effect group. The perspective with the highest positive (Ri – Ci) value has a direct influence on other perspectives. Hence, in this study, Industry (P2) is identified as the most critical factor, exerting a direct impact on the other perspectives, namely P1, P3, and P4. Conversely, the perspective with the highest negative (Ri – Ci) value is the one most influenced by the other perspectives. Therefore, Civil Society (P4) is found to be the most affected by P1, P2, and P3.

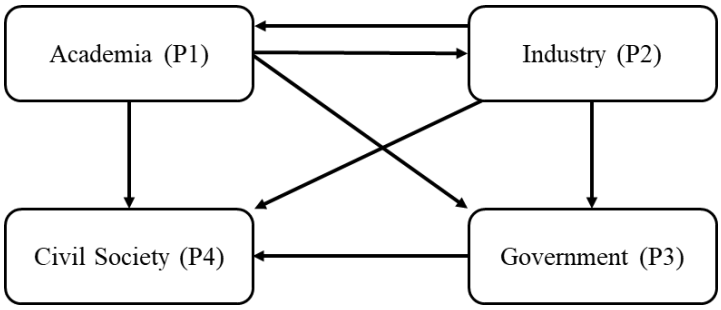


Figure 6.10: The Visualization of the Interactions among Perspectives of Construction 4.0 Innovation Ecosystem.

Table 6.8 presents the effects of the components within the Academia perspective (P1). Among these, A2 is identified as the most significant component, having the highest (Ri + Ci) value of 20.19, while A4 is the least significant, with the lowest (Ri + Ci) value of 19.17. Consequently, the ranking of the five components is A2 > A5 > A3 > A1 > A4. As per Table 6.8, based on (Ri – Ci) values, components A3, A4, and A5 fall under the effect group, whereas A1 and A2 belong to the cause group. With the highest positive (Ri – Ci) value of 1.08, A1 is identified as the most critical factor, exerting a direct impact on other components within the Academia perspective. Conversely, A4, with the highest negative (Ri – Ci) value of -1.07, is the most influenced component within this perspective.

Within the Industry perspective (P2), components I1 and I2 are identified as the most significant, each having the highest (Ri + Ci) value of 60.94, while I4 is the least significant, with the lowest (Ri + Ci) value of 58.83. Consequently, the ranking of the four components in the industry perspective is I1 & I2 > I3 > I4. As indicated in Table 6.8, based on (Ri – Ci) values, I4 belongs to the effect group, whereas I1, I2, and I3 fall under the cause group. With the highest positive (Ri – Ci) value of 0.90, I3 is recognized as the most critical factor, exerting a direct influence on the other components within the industry perspective. Conversely, I4, with the highest negative (Ri – Ci) value of -2.45, is the most affected component within this perspective. Within the Government perspective (P3), G2 is identified as the most significant sub-component, having the highest (Ri + Ci) value of 30.79, while G4 is the least significant, with the lowest (Ri + Ci) value of 30.46. As a result, the ranking of the five components is G2 > G5 > G3 > G1 > G4. As per Table 6.8, based on (Ri – Ci) values, G3, G4, and G5 belong to the effect group, whereas G1 and G2 fall under the cause group. With the highest positive (Ri – Ci) value of 1.65, G1 is identified as the most critical factor, exerting a direct influence on the other components within the Government perspective. Conversely, G5, with the highest

negative (Ri – Ci) value of -0.78, is the most influenced component in this perspective. Within the Civil Society perspective (P4), C2 is identified as the most significant component, having the highest (Ri + Ci) value of 123.47, while C3 is the least significant, with the lowest (Ri + Ci) value of 118.99. Consequently, the ranking of the four components is C2 > C1 > C4 > C3. As per Table 6.8, based on (Ri – Ci) values, C2 and C4 fall into the effect group, whereas C1 and C3 belong to the cause group. With the highest positive (Ri – Ci) value of 3.72, C3 is recognized as the most critical factor, exerting a direct influence on the other components within the Civil Society perspective. Conversely, C4, with the highest negative (Ri – Ci) value of -2.58, is the most influenced component in this perspective.

Table 6.8: Effects and Ranking of Perspective's Components

Code	Ri+Ci	Ri-Ci	Identity	Ranking within Perspective	Overall Ranking
A1	19.51	1.08	Cause	4	16
A2	20.19	1.06	Cause	1	13
A3	19.63	-0.29	Effect	3	15
A4	19.17	-1.07	Effect	5	17
A5	19.73	-0.78	Effect	2	14
I1	60.94	0.79	Cause	1	5
I2	60.94	0.76	Cause	1	5
I3	59.94	0.90	Cause	2	6
I4	58.83	-2.45	Effect	3	7
G1	30.53	1.65	Cause	4	11
G2	30.79	0.49	Cause	1	8
G3	30.54	-0.73	Effect	3	10
G4	30.46	-0.63	Effect	5	12
G5	30.61	-0.78	Effect	2	9
C1	121.64	1.08	Cause	2	2
C2	123.47	-2.22	Effect	1	1
C3	118.99	3.72	Cause	4	4
C4	120.85	-2.58	Effect	3	3

6.3.1 Construction 4.0 Innovation Ecosystem Framework

Figure 6.11 shows the Construction 4.0 Innovation Ecosystem Framework. It is structured around the Quadruple Helix Model, which integrates four key components Academia, Industry, Government, and Civil Society. Each key component plays a crucial role in driving the adoption and implementation of Construction 4.0 technologies. These components interact by facilitating knowledge creation, workforce development, policy support, technological transformation, and social acceptance. It also ensures a holistic approach toward digital innovation in the construction sector. Academia is the foundation for knowledge creation, skill development, and workforce readiness for Construction 4.0. Research and Development (R&D) in Construction 4.0 technologies fosters innovation by exploring advanced solutions such as Building Information Modeling (BIM), Digital Twins, AI-driven construction management, and automation. Further, applied research in sustainability and smart cities ensures that new technologies contribute to energy efficiency, climate resilience, and sustainable urbanization. The incubation centres and startup ecosystems within academic

institutions promote entrepreneurial activities. These activities support innovators in developing and commercializing new technologies.

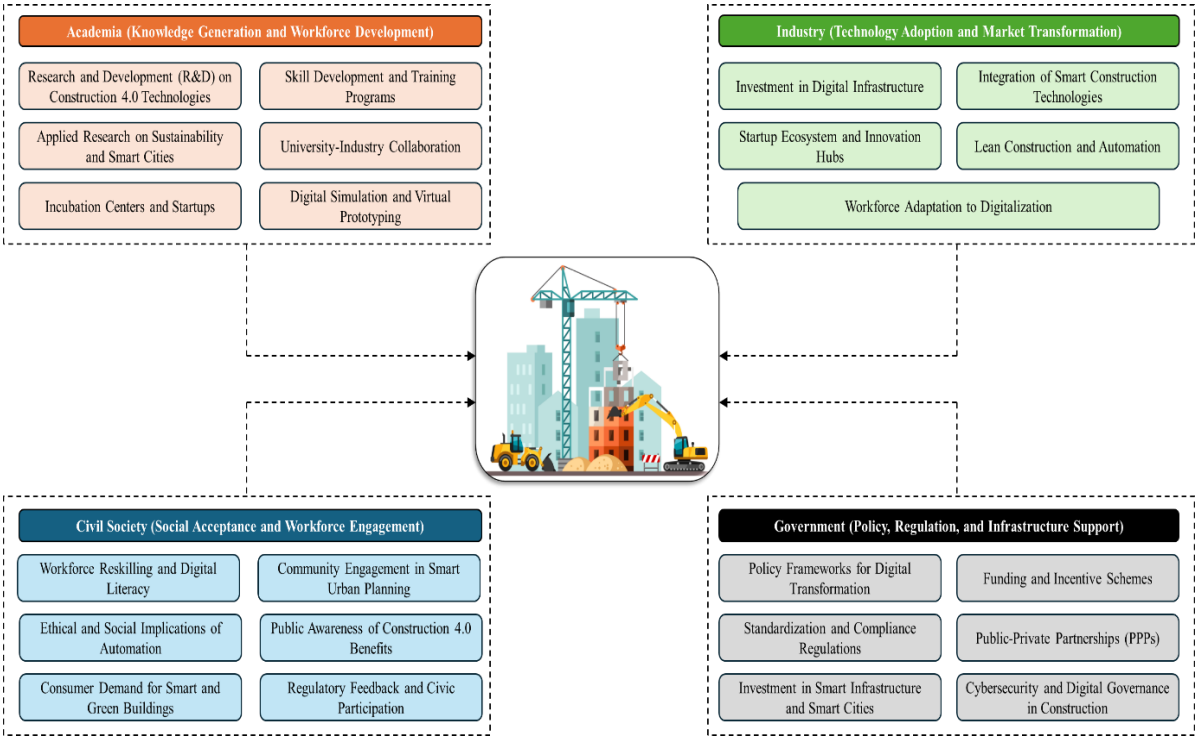

Academia (Knowledge Generation and Workforce Development)
Research and Development (R&D) on Construction 4.0 Technologies
Skill Development and Training Programs
Applied Research on Sustainability and Smart Cities
University-Industry Collaboration
Incubation Centers and Startups
Digital Simulation and Virtual Prototyping
Industry (Technology Adoption and Market Transformation)
Investment in Digital Infrastructure
Integration of Smart Construction Technologies
Startup Ecosystem and Innovation Hubs
Lean Construction and Automation
Workforce Adaptation to Digitalization
Civil Society (Social Acceptance and Workforce Engagement)
Workforce Reskilling and Digital Literacy
Community Engagement in Smart Urban Planning
Ethical and Social Implications of Automation
Public Awareness of Construction 4.0 Benefits
Consumer Demand for Smart and Green Buildings
Regulatory Feedback and Civic Participation
Government (Policy, Regulation, and Infrastructure Support)
Policy Frameworks for Digital Transformation
Funding and Incentive Schemes
Standardization and Compliance Regulations
Public-Private Partnerships (PPPs)
Investment in Smart Infrastructure and Smart Cities
Cybersecurity and Digital Governance in Construction

Figure 6.11: Construction 4.0 Innovation Ecosystem Framework.

Moreover, university-industry collaboration bridges the gap between theoretical research and practical application, enabling industries to access cutting-edge knowledge while offering students hands-on experience. Skill development and training programs equip the workforce with competencies in robotics, IoT, cloud computing, and digital construction tools. Digital simulation and virtual prototyping enhance experiential learning and design optimization. The construction industry is the primary driver of technological transformation. The leveraging of the technological transformation is for the digital innovations to enhance efficiency, safety, and sustainability. Investing in digital infrastructure helps integrate IoT-enabled sensors, AI automation, and real-time data analytics. This improves efficiency in construction. Startups and innovation hubs support the rapid growth of Construction 4.0 solutions. They encourage both competition and collaboration among tech-driven firms. Smart construction technologies like 3D printing, autonomous machines, and prefabrication boost productivity. They also reduce project timelines. Lean construction and automation remove inefficiencies. They cut down waste and improve resource use. Workforce adaptation is essential for successful digital adoption. Professionals must learn to use digital tools and modern construction methods effectively. The government plays a key role in supporting Construction 4.0. It shapes regulations and provides an infrastructure to help adoption. Policies for digital transformation guide the use of new technologies in construction. Standard rules ensure the safety, quality, and smooth integration of digital tools. Compliance regulations help different systems work together across projects. Investment in smart infrastructure speeds up the use of connected construction technologies. It also supports sustainable and strong urban development. Financial aid, like funding and incentives, helps firms cover the initial costs of digital adoption. Public-Private Partnerships (PPPs) improve cooperation between the government and private companies. This ensures large infrastructure projects run efficiently.

Cybersecurity is also important in digital construction. It protects project data and critical infrastructure from cyber threats. Strong digital governance maintains the reliability and security of construction platforms. The success of Construction 4.0 depends on public acceptance and workforce readiness. Workers need new skills to adapt to digital tools. Training programs help them learn essential digital skills. This makes the shift to new technology easier. Communities play a role in smart urban planning. Public input helps create better infrastructure projects. Awareness campaigns explain the benefits of Construction 4.0. These include better building quality, less environmental harm, and improved city living. Automation raises concerns about job loss. It is important to address these issues. Ethical use of AI ensures fair and responsible automation in construction. People want smart and eco-friendly buildings. This demand pushes the industry to adopt green technologies. Energy efficiency and sustainable practices become more important. Regulations should reflect public needs. Feedback from citizens helps shape policies. This ensures that new construction technologies align with society's expectations.

6.3.2 Bridging Construction 4.0 and 5.0: Academia Extensions

While this research primarily focused on developing the Construction 4.0 innovation ecosystem framework across the four perspectives of academia, industry, government, and civil society, it also opens avenues for exploring the transition toward Industry 5.0 principles in the construction sector. Industry 4.0 is strongly oriented toward technological development, whereas Industry 5.0 emphasizes human-centricity, inclusiveness, and collaboration between humans and machines. This paradigm shift is particularly relevant for the academia perspective, where the preparation of future workforce and knowledge dissemination directly influence the long-term adoption of emerging technologies in construction.

As part of extension work under Research Objective 3, preliminary studies have been undertaken to investigate how academic institutions can align themselves with Industry 4.0 and 5.0 competencies. One such study focused on the integration of Industry 4.0 technologies within higher education (Education 4.0), highlighting the role of immersive technologies such as AR/VR, IoT, simulation, and data analytics in fostering new learning experiences. This study underlined that while Industry 4.0-driven education enhances technological skills, the evolution toward Industry 5.0 requires a parallel focus on creativity, collaboration, problem-solving, and inclusivity in pedagogy.

Further extension work examined curricular reforms and inclusive pedagogical approaches necessary for Industry 5.0. It emphasized bridging the digital divide, promoting diversity and inclusion, empowering educators with digital competencies, and integrating project-based and blended learning models. These insights reinforce the human-centric dimension of Industry 5.0 and suggest that academia can play a transformative role in equipping professionals with both technical expertise and socio-emotional skills required in the next industrial era.

Taken together, these extension works strengthen the argument that the Construction 4.0 innovation ecosystem framework can serve as a foundation for future research on Construction 5.0. Specifically, the academia perspective can be expanded to incorporate inclusive and human-centric educational models that prepare the workforce not only for technological adoption but also for ethical, sustainable, and collaborative practices. Future studies may extend similar approaches across industry, government, and civil society perspectives to fully realize the transition from Construction 4.0 to Construction 5.0.

7. CONCLUSIONS

The present research highlights the transformative potential of Construction 4.0 technologies in reshaping the construction industry, with Building Information Modeling (BIM) emerging as the most widely adopted and influential technology among them. Other technologies such as cloud computing, big data analytics, and cyber security are yet to be used in the construction industry. This study has mapped the current landscape of research and the extent of adoption of Construction 4.0 enabling technologies, evaluating their impact on construction processes and outcomes. A Strategic Framework has been formulated to guide the successful implementation of these technologies, addressing the critical need for structured deployment practices. Furthermore, the research identifies and prioritizes key barriers hindering adoption, with High Initial Cost ranking as the most significant barrier. A dedicated Barrier Management Framework is proposed to mitigate these challenges effectively. The study also explores that the understanding of concept, motivating factors for Construction 4.0 implementation, and barriers associated with Construction 4.0 implementation has significant impact on success of Construction 4.0. The Construction 4.0 innovation ecosystem reveals the pivotal role of the industry, not only as a core driver but also in shaping other entities within the ecosystem. Academia and industry exhibit a strong bidirectional interaction, fostering mutual growth, while governmental responses are primarily shaped by academic and industrial inputs. Civil society, in turn, is influenced collectively by academia, industry, and government. These interdependencies underscore the importance of a collaborative and informed approach for Construction 4.0 to thrive. Overall, the findings of this research increase the knowledge and awareness concerning the Construction 4.0 implementation and sustainability in construction industries. It has been found that an organization's vision plays important role in implementation of Construction 4.0. Organizations should focus on the development of a construction processes based on the Construction 4.0 concept without delocalizing or moving to low-cost construction processes. Therefore, summary of various benefits to society is as follows:

- The current research will provide the useful solution and guideline for the construction industries to develop the strategy to overcome the barriers associated with the Construction 4.0 concept.
- This research will help construction industries to improve their processes, services and operations which will gain customer confidence and the faith in the company; this in turn will help to secure key position in the market.
- This research will provide the new dimension to the academia which will help in modeling their teaching aligned with the requirement of industry. Table 7.1 shows the mapping of research objectives and research deliverables.

Table 7.1: Research Objectives vs. Research Deliverables

ROs	Research Deliverables	Description
RO1	RD1: Determination of Research & Adoption Scenario of Construction 4.0 Enabling Technologies	BIM is the most widely adopted Construction 4.0 technology. However, Digital Twins, the Internet of Things (IoT), Smart Sensors, and 3D printing have the potential to support the Construction 4.0 concept whereas applications of machine learning, autonomous robotics, and augmented/virtual reality still offer plenty of opportunities for future applied research. Then the framework for the effective implementation of Construction 4.0 is proposed. This framework consists of eight steps named as strategic planning and vision setting, technology selection and integration, organizational change management, workforce development and culture change, pilot projects and scaling, data management, continuous improvement and innovation, and collaboration and ecosystem development. Finally, the proposed framework is implemented in construction industry to check its validity. The focus was on small tasks that can bring faith and belief in Construction 4.0 concept.
	RD2: Development of Strategic Framework for Construction 4.0 Implementation	
	RD3: Implementation of Proposed Framework (Case Study)	
RO2	RD4: Analysis of Barriers associated with the Implementation of Construction 4.0	34 barriers related to the adoption of Construction 4.0 were identified through a literature review of peer-reviewed journal articles and construction industry experts. These barriers are prioritized by using TOPSIS method. High Initial Cost and Internal Communication Issues are the top-ranked barriers. Then, the strategies to overcome these barriers were proposed and their effectiveness was evaluated. Finally, a barrier management framework was proposed.
RO3	RD5: Development of Construction 4.0 Innovation Ecosystem Framework	04 perspectives and their 18 components within the Construction 4.0 innovation ecosystem framework were identified through a systematic review of peer-reviewed journal articles. Subsequently, the significance of these perspectives and components and their causal relationships is examined using the DEMATEL method. As an extension, the academia perspective was further examined in the context of Industry 5.0. The research highlighted the transition from technology-centric approaches of Industry 4.0 toward human-centric principles such as inclusivity, creativity, and digital equity. This extension reinforces academia's role in preparing the future workforce and provides a foundation for advancing research toward Construction 5.0.

8. FUTURE SCOPE

The limitation of this study is a deficiency of industries using the Construction 4.0 concept. In this research work, conclusions are made based on the data collected through the questionnaire and expert interviews. The quality of such data can be problematic up to some extent since the opinions and knowledge of participants are not fixed and the interpretation of those opinions is likely to vary. Future scopes are as follows:

- The tools used for barrier analysis and Construction 4.0 innovation ecosystem can be validated by using different methods.
- It is suggested to focus on the horizontal deployment of the proposed strategic framework to assess its effectiveness and scalability across different operational settings.
- Apply the framework in large industries to assess its fit with existing systems and its impact on efficiency, safety, and compliance at scale.
- Role of academia, industry, government and civil society can be explored collectively for successful adoption of Industry 5.0 principles in construction industry.

9. PUBLICATIONS

❖ ***International Journal Publications***

- **P. Dhamak**, P. Aital, and A. Daftardar, "A comprehensive overview of Construction 4.0 technologies and their implementation in the construction industry," *Journal of Science and Technology Policy Management*, 2025, doi: 10.1108/JSTPM-09-2023-0162. *(addressing RO1)*
- **P. Dhamak**, P. Aital, and A. Daftardar, "Strategic management of barriers in the adoption of Construction 4.0: TOPSIS and 5W2H approach for sustainable development goal integration," *International Journal of Organizational Analysis*, 2025, doi: 10.1108/IJOA-12-2024-5114. *(addressing RO2)*
- **P. Dhamak**, P. Aital, and A. Daftardar, "Navigating the digital transformation: examining the implementation landscape of Construction 4.0 enabling technologies," *International Journal of Organizational Analysis*, 2025. ***(Accepted for Publication)*** *(addressing RO1)*
- **P. Dhamak**, A. Benslimane, B. Pasi, P. Aital, A. Daftardar, and S. Rane, "Aerial innovation: a comprehensive review on integration of unmanned aerial vehicles in modern construction practices," *International Journal of Intelligent Unmanned Systems*, 2025. ***(Under Review)*** *(addressing RO1)*
- **P. Dhamak**, A. Kumar, A. Daftardar, and S. Rane, "Development of an innovation ecosystem framework for Construction 4.0: a quadruple helix approach," *Asian Education and Development Studies*, 2025. ***(Under Review)*** *(addressing RO3)*

❖ ***Conference Publications***

- Presented research paper on topic "Preparing for Industry 5.0: Inclusive Curricular Approaches and Digital Empowerment" in the 6th International Conference on Advanced Technologies for Humanity (2024) organized by the University of Salerno (Italy) in collaboration with the Ecole Marocaine des Sciences de l'Ingénieur (EMSI), the National Institute of Statistics and Applied Economics (INSEA), the National Institute of Post and Telecommunication (INPT), the Faculty of Sciences of Mohammed V University in Rabat (UM5-FSR), the Ecole Nationale des Sciences Appliquées (ENSA-Kenitra) and the Ecole Nationale Supérieure des Mines de Rabat (ENSMR). *(addressing RO3)*

❖ ***Book Chapter Publications***

- P. S. Dhamak, P. Aital, and A. Daftardar, "Navigating Inclusion in the Industry 4.0 Horizon," 2024, pp. 163–186. doi: 10.4018/979-8-3693-4058-5.ch007. *(addressing RO3)*

❖ ***Patents***

- Filed Indian Standard Patent (Product Innovation) titled "An Internet-of-Things (IoT)-Based Wearable Assembly to Monitor and Warn a User", Patent Application No. 202521002069, 09th January 2025, India. *(Published on 07/02/2025) (addressing RO1)*

10. REFERENCES

[1] D. Rani, N. S. Gill, and P. Gulia, "A forensic framework to improve digital image evidence administration in IIoT," *J Ind Inf Integr*, vol. 38, Mar. 2024, doi: 10.1016/j.jii.2024.100568.

[2] L. G. M. Bispo and F. G. Amaral, "The impact of Industry 4.0 on occupational health and safety: A systematic literature review," *J Safety Res*, vol. 90, pp. 254–271, Sep. 2024, doi: 10.1016/j.jsr.2024.04.009.

[3] S. A. Shah, D. Z. Seker, S. Hameed, and D. Draheim, "The rising role of big data analytics and IoT in disaster management: Recent advances, taxonomy and prospects," *IEEE Access*, vol. 7, pp. 54595–54614, 2019, doi: 10.1109/ACCESS.2019.2913340.

[4] A. Baratta, A. Cimino, F. Longo, and L. Nicoletti, "Digital twin for human-robot collaboration enhancement in manufacturing systems: Literature review and direction for future developments," *Comput Ind Eng*, vol. 187, Jan. 2024, doi: 10.1016/j.cie.2023.109764.

[5] P. V. R. P. Raj, S. K. Jauhar, M. Ramkumar, and S. Pratap, "Procurement, traceability and advance cash credit payment transactions in supply chain using blockchain smart contracts," *Comput Ind Eng*, vol. 167, May 2022, doi: 10.1016/j.cie.2022.108038.

[6] P. Davis, F. Aziz, M. T. Newaz, W. Sher, and L. Simon, "The classification of construction waste material using a deep convolutional neural network," *Autom Constr*, vol. 122, Feb. 2021, doi: 10.1016/j.autcon.2020.103481.

[7] R. Woitsch, A. Sumereder, and D. Falcioni, "Model-based data integration along the product & service life cycle supported by digital twinning," *Comput Ind*, vol. 140, Sep. 2022, doi: 10.1016/j.compind.2022.103648.

[8] M. Insa-Iglesias, M. D. Jenkins, and G. Morison, "3D visual inspection system framework for structural condition monitoring and analysis," *Autom Constr*, vol. 128, Aug. 2021, doi: 10.1016/j.autcon.2021.103755.

[9] H. Golpîra, S. A. R. Khan, and S. Safaeipour, "A review of logistics Internet-of-Things: Current trends and scope for future research," *J Ind Inf Integr*, vol. 22, Jun. 2021, doi: 10.1016/j.jii.2020.100194.

[10] D. Gürdür Broo, U. Boman, and M. Törngren, "Cyber-physical systems research and education in 2030: Scenarios and strategies," *J Ind Inf Integr*, vol. 21, Mar. 2021, doi: 10.1016/j.jii.2020.100192.

[11] M. J. Spaniol and N. J. Rowland, "Business ecosystems and the view from the future: The use of corporate foresight by stakeholders of the Ro-Ro shipping ecosystem in the Baltic Sea Region," *Technol Forecast Soc Change*, vol. 184, Nov. 2022, doi: 10.1016/j.techfore.2022.121966.

[12] Q. Zhu, J. Du, Y. Shi, and P. Wei, "Neurobehavioral assessment of force feedback simulation in industrial robotic teleoperation," *Autom Constr*, vol. 126, Jun. 2021, doi: 10.1016/j.autcon.2021.103674.

[13] D. Zhang, C. Zhan, L. Chen, Y. Wang, and G. Li, “An in-situ detection method for assessing the thermal transmittance of building exterior walls using unmanned aerial vehicle–infrared thermography (UAV-IRT),” *Journal of Building Engineering*, vol. 91, Aug. 2024, doi: 10.1016/j.jobe.2024.109724.

[14] S. Wang, W. Sun, and M. Huang, “An adaptive large neighborhood search for the multi-depot dynamic vehicle routing problem with time windows,” *Comput Ind Eng*, vol. 191, May 2024, doi: 10.1016/j.cie.2024.110122.

[15] T. Su, H. Li, and Y. An, “A BIM and machine learning integration framework for automated property valuation,” *Journal of Building Engineering*, vol. 44, Dec. 2021, doi: 10.1016/j.jobe.2021.102636.

[16] R. Mendoza-Gómez and R. Z. Ríos-Mercado, “Location of primary health care centers for demand coverage of complementary services,” *Comput Ind Eng*, vol. 169, Jul. 2022, doi: 10.1016/j.cie.2022.108237.

[17] C. Sandeepa, B. Siniarski, N. Kourtellis, S. Wang, and M. Liyanage, “A survey on privacy for B5G/6G: New privacy challenges, and research directions,” *J Ind Inf Integr*, vol. 30, Nov. 2022, doi: 10.1016/j.jii.2022.100405.

[18] L. Kim, E. Yahia, F. Segonds, P. Véron, and A. Mallet, “i-Dataquest: A heterogeneous information retrieval tool using data graph for the manufacturing industry,” *Comput Ind*, vol. 132, Nov. 2021, doi: 10.1016/j.compind.2021.103527.

[19] S. Su, C. Yu, Y. Jiang, K. Kang, and R. Y. Zhong, “Trading building demolition waste via digital twins,” *Autom Constr*, vol. 156, Dec. 2023, doi: 10.1016/j.autcon.2023.105105.

[20] S. Agnisarman *et al.*, “Sensemaking perspective on infrastructure risk-related mental model development of windstorm loss prevention engineers,” *Journal of Building Engineering*, vol. 52, Jul. 2022, doi: 10.1016/j.jobe.2022.104314.

[21] T. V. Le and R. Fan, “Digital twins for logistics and supply chain systems: Literature review, conceptual framework, research potential, and practical challenges,” *Comput Ind Eng*, vol. 187, Jan. 2024, doi: 10.1016/j.cie.2023.109768.

[22] N. Li, Y. Wang, W. Geng, and Z. Li, “Enhancing extraction of two-dimensional engineering drawings from three-dimensional data of existing buildings,” *Journal of Building Engineering*, vol. 76, Oct. 2023, doi: 10.1016/j.jobe.2023.107235.

[23] N. Knoth, A. Tolzin, A. Janson, and J. M. Leimeister, “AI literacy and its implications for prompt engineering strategies,” *Computers and Education: Artificial Intelligence*, vol. 6, Jun. 2024, doi: 10.1016/j.caeai.2024.100225.

[24] O. Kolade and A. Owoseni, “Employment 5.0: The work of the future and the future of work,” *Technol Soc*, vol. 71, Nov. 2022, doi: 10.1016/j.techsoc.2022.102086.

[25] R. Rudek, “A generic optimization framework for scheduling problems under machine deterioration and maintenance activities,” *Comput Ind Eng*, vol. 174, Dec. 2022, doi: 10.1016/j.cie.2022.108800.

[26] R. Pitakaso, K. Sethanan, and T. Jamrus, “Hybrid PSO and ALNS algorithm for software and mobile application for transportation in ice manufacturing industry 3.5,” *Comput Ind Eng*, vol. 144, Jun. 2020, doi: 10.1016/j.cie.2020.106461.

[27] S. Palaniyappan, G. Annamalai, N. kumar Sivakumar, and P. Muthu, “Development of functional gradient multi-material composites using Poly Lactic Acid and walnut shell reinforced Poly Lactic Acid filaments by fused filament fabrication technology,” *Journal of Building Engineering*, vol. 65, Apr. 2023, doi: 10.1016/j.jobe.2022.105746.

[28] M. Foroughi Sabzevar, M. Gheisari, and L. J. Lo, “AR-QR code for improving crew access to design and construction information,” *Autom Constr*, vol. 154, Oct. 2023, doi: 10.1016/j.autcon.2023.105017.

[29] K. Ćmielewski, P. Gołuch, J. Kuchmister, I. Wilczyńska, B. Ćmielewski, and O. Grzeja, “Detection of crane track geometric parameters using UAS,” *Autom Constr*, vol. 128, Aug. 2021, doi: 10.1016/j.autcon.2021.103751.

[30] S. Halder, K. Afsari, E. Chiou, R. Patrick, and K. A. Hamed, “Construction inspection & monitoring with quadruped robots in future human-robot teaming: A preliminary study,” *Journal of Building Engineering*, vol. 65, Apr. 2023, doi: 10.1016/j.jobe.2022.105814.

[31] Y. Jiang, M. Li, D. Guo, W. Wu, R. Y. Zhong, and G. Q. Huang, “Digital twin-enabled smart modular integrated construction system for on-site assembly,” *Comput Ind*, vol. 136, Apr. 2022, doi: 10.1016/j.compind.2021.103594.

[32] R. Czyba, J. Domin, and M. Górski, “Docking unmanned multi-rotor platform for the diagnostic of building structures strengthened with fiber-reinforced polymer overlays,” *Autom Constr*, vol. 159, Mar. 2024, doi: 10.1016/j.autcon.2023.105256.

[33] A. Grybauskas, A. Stefanini, and M. Ghobakhloo, “Social sustainability in the age of digitalization: A systematic literature Review on the social implications of industry 4.0,” *Technol Soc*, vol. 70, Aug. 2022, doi: 10.1016/j.techsoc.2022.101997.

[34] F. Elghaish, F. Pour Rahimian, M. R. Hosseini, D. Edwards, and M. Shelbourn, “Financial management of construction projects: Hyperledger fabric and chaincode solutions,” *Autom Constr*, vol. 137, May 2022, doi: 10.1016/j.autcon.2022.104185.

[35] M. Abdeldayem, A. Baqi, and S. Aldulaimi, “Empowering stakeholder engagement and decision-making in future nuclear organisations: a multilevel research framework for challenges and opportunities,” *International Journal of Organizational Analysis*, 2024, doi: 10.1108/IJOA-07-2024-4644.

[36] I. Laskurain-Iturbe, G. Arana-Landín, B. Landeta-Manzano, and N. Uriarte-Gallastegi, “Exploring the influence of industry 4.0 technologies on the circular economy,” *J Clean Prod*, vol. 321, Oct. 2021, doi: 10.1016/j.jclepro.2021.128944.

[37] A. Zhu, P. Pauwels, and B. De Vries, “Smart component-oriented method of construction robot coordination for prefabricated housing,” *Autom Constr*, vol. 129, Sep. 2021, doi: 10.1016/j.autcon.2021.103778.

[38] S. Fareri, G. Fantoni, F. Chiarello, E. Coli, and A. Binda, “Estimating Industry 4.0 impact on job profiles and skills using text mining,” *Comput Ind*, vol. 118, Jun. 2020, doi: 10.1016/j.compind.2020.103222.

[39] R. J. Thomas, G. O’Hare, and D. Coyle, “Understanding technology acceptance in smart agriculture: A systematic review of empirical research in crop production,” *Technol Forecast Soc Change*, vol. 189, Apr. 2023, doi: 10.1016/j.techfore.2023.122374.

[40] V. Shcherbakov and G. Silkina, “Supply chain management open innovation: Virtual integration in the network logistics system,” *Journal of Open Innovation: Technology, Market, and Complexity*, vol. 7, no. 1, pp. 1–21, Mar. 2021, doi: 10.3390/joitmc7010054.

[41] S. Shokouhyar, S. Shokoohyar, A. Sobhani, and A. J. Gorizi, “Shared mobility in post-COVID era: New challenges and opportunities,” *Sustain Cities Soc*, vol. 67, Apr. 2021, doi: 10.1016/j.scs.2021.102714.

[42] A. Raj, A. A. Mukherjee, A. B. L. de Sousa Jabbour, and S. K. Srivastava, “Supply chain management during and post-COVID-19 pandemic: Mitigation strategies and practical lessons learned,” *J Bus Res*, vol. 142, pp. 1125–1139, Mar. 2022, doi: 10.1016/j.jbusres.2022.01.037.

[43] O. A. Ejohwomu, O. S. Oshodi, and K. C. Lam, “Nigeria’s construction industry: Barriers to effective communication,” *Engineering, Construction and Architectural Management*, vol. 24, no. 4, pp. 652–667, 2017, doi: 10.1108/ECAM-01-2016-0003.

[44] by A. Adebayo Fashina *et al.*, “The major barriers to the implementation of project management in small and medium construction companies in Hargeisa 1,” 2020. [Online]. Available: www.pmworldlibrary.net

[45] S. O. Ametepey, E. Y. F. Jnr, and J. E. Cobbina, “Barriers to the Growth of Small and Medium Scale Construction Enterprises in Ghana,” *Open Journal of Civil Engineering*, vol. 12, no. 01, pp. 38–55, 2022, doi: 10.4236/ojce.2022.121004.

[46] D. Bendig, C. Schulz, L. Theis, and S. Raff, “Digital orientation and environmental performance in times of technological change,” *Technol Forecast Soc Change*, vol. 188, Mar. 2023, doi: 10.1016/j.techfore.2022.122272.

[47] F. Lanzalonga, M. Oppioli, F. Dal Mas, and S. Secinaro, “Drones in Venice: Exploring business model applications for disruptive mobility and stakeholders’ value proposition,” *J Clean Prod*, vol. 423, Oct. 2023, doi: 10.1016/j.jclepro.2023.138764.

[48] T. Briard, C. Jean, A. Aoussat, and P. Véron, “Challenges for data-driven design in early physical product design: A scientific and industrial perspective,” *Comput Ind*, vol. 145, Feb. 2023, doi: 10.1016/j.compind.2022.103814.

[49] D. Yao and B. García de Soto, “Enhancing cyber risk identification in the construction industry using language models,” *Autom Constr*, vol. 165, Sep. 2024, doi: 10.1016/j.autcon.2024.105565.

[50] G. Yilmaz, L. Salter, D. McFarlane, and B. Schönfuß, “Low-cost (Shoestring) digital solution areas for enabling digitalisation in construction SMEs,” *Comput Ind*, vol. 150, Sep. 2023, doi: 10.1016/j.compind.2023.103941.

[51] B. H. Ojeda Rios, E. C. Xavier, F. K. Miyazawa, P. Amorim, E. Curcio, and M. J. Santos, "Recent dynamic vehicle routing problems: A survey," *Comput Ind Eng*, vol. 160, Oct. 2021, doi: 10.1016/j.cie.2021.107604.

[52] S. Y. Tan, A. Taeihagh, and A. Tripathi, "Tensions and antagonistic interactions of risks and ethics of using robotics and autonomous systems in long-term care," *Technol Forecast Soc Change*, vol. 167, Jun. 2021, doi: 10.1016/j.techfore.2021.120686.

[53] R. García, J. Aguilar, M. Toro, N. Pérez, A. Pinto, and P. Rodríguez, "Autonomic computing in a beef-production process for Precision Livestock Farming," *J Ind Inf Integr*, vol. 31, Feb. 2023, doi: 10.1016/j.jii.2022.100425.

[54] D. G. Broo, J. C. Gellers, and H. S. Sætra, "Re-imagining intelligent machines in an anthropocentric-ecocentric continuum: The case for ecocentric intelligent machines," *J Ind Inf Integr*, vol. 41, Sep. 2024, doi: 10.1016/j.jii.2024.100636.

[55] G. Singh, R. Rajesh, Y. Daultani, and S. C. Misra, "Resilience and sustainability enhancements in food supply chains using Digital Twin technology: A grey causal modelling (GCM) approach," *Comput Ind Eng*, vol. 179, May 2023, doi: 10.1016/j.cie.2023.109172.

[56] D. G. Broo, "Transdisciplinarity and three mindsets for sustainability in the age of cyber-physical systems," *J Ind Inf Integr*, vol. 27, May 2022, doi: 10.1016/j.jii.2021.100290.

[57] B. S. Abdulfattah *et al.*, "Predicting implications of design changes in BIM-based construction projects through machine learning," *Autom Constr*, vol. 155, Nov. 2023, doi: 10.1016/j.autcon.2023.105057.

[58] Ž. Turk, B. García de Soto, B. R. K. Mantha, A. Maciel, and A. Georgescu, "A systemic framework for addressing cybersecurity in construction," *Autom Constr*, vol. 133, Jan. 2022, doi: 10.1016/j.autcon.2021.103988.

[59] A. Hadavi and S. Alizadehsalehi, "From BIM to metaverse for AEC industry," *Autom Constr*, vol. 160, Apr. 2024, doi: 10.1016/j.autcon.2023.105248.

[60] I. de la Peña Zarzuelo, M. J. Freire Soeane, and B. López Bermúdez, "Industry 4.0 in the port and maritime industry: A literature review," *J Ind Inf Integr*, vol. 20, Dec. 2020, doi: 10.1016/j.jii.2020.100173.

[61] B. Elkhapery, R. Pěnička, M. Němec, and M. Siddiqui, "Metaheuristic planner for cooperative multi-agent wall construction with UAVs," *Autom Constr*, vol. 152, Aug. 2023, doi: 10.1016/j.autcon.2023.104908.

[62] T. Bastos, L. C. Teixeira, and L. J. R. Nunes, "Forest 4.0: Technologies and digitalization to create the residual biomass supply chain of the future," *J Clean Prod*, vol. 467, Aug. 2024, doi: 10.1016/j.jclepro.2024.143041.

[63] E. Lucchi, "Digital twins for the automation of the heritage construction sector," *Autom Constr*, vol. 156, Dec. 2023, doi: 10.1016/j.autcon.2023.105073.

[64] F. Chiarello, G. Fantoni, T. Hogarth, V. Giordano, L. Baltina, and I. Spada, "Towards ESCO 4.0 – Is the European classification of skills in line with Industry 4.0? A text

mining approach," *Technol Forecast Soc Change*, vol. 173, Dec. 2021, doi: 10.1016/j.techfore.2021.121177.

[65] S. Perera, X. Jin, P. Das, K. Gunasekara, and M. Samaratunga, "A strategic framework for digital maturity of design and construction through a systematic review and application," *J Ind Inf Integr*, vol. 31, Feb. 2023, doi: 10.1016/j.jii.2022.100413.

[66] T. D. Moshood, J. O. Rotimi, W. Shahzad, and J. A. Bamgbade, "Infrastructure digital twin technology: A new paradigm for future construction industry," *Technol Soc*, vol. 77, Jun. 2024, doi: 10.1016/j.techsoc.2024.102519.

[67] A. J. McNamara and S. M. E. Sepasgozar, "Intelligent contract adoption in the construction industry: Concept development," *Autom Constr*, vol. 122, Feb. 2021, doi: 10.1016/j.autcon.2020.103452.

[68] S. Anand, M. Enayati, D. Raj, A. Montresor, and M. V. Ramesh, "Internet over the ocean: A smart IoT-enabled digital ecosystem for empowering coastal fisher communities," *Technol Soc*, vol. 79, Dec. 2024, doi: 10.1016/j.techsoc.2024.102686.

[69] F. Freddi *et al.*, "Innovations in earthquake risk reduction for resilience: Recent advances and challenges," *International Journal of Disaster Risk Reduction*, vol. 60, Jun. 2021, doi: 10.1016/j.ijdrr.2021.102267.

[70] G. Narkhede, B. Pasi, N. Rajhans, and A. Kulkarni, "Industry 5.0 and the future of sustainable manufacturing: A systematic literature review," Dec. 01, 2023, *John Wiley and Sons Inc*. doi: 10.1002/bsd2.272.

[71] O. Sánchez, K. Castañeda, S. Vidal-Méndez, D. Carrasco-Beltrán, and N. E. Lozano-Ramírez, "Exploring the influence of linear infrastructure projects 4.0 technologies to promote sustainable development in smart cities," *Results in Engineering*, vol. 23, Sep. 2024, doi: 10.1016/j.rineng.2024.102824.

[72] G. B. Narkhede, B. N. Pasi, N. Rajhans, and A. Kulkarni, "Industry 5.0 and sustainable manufacturing: a systematic literature review," *Benchmarking*, Feb. 2024, doi: 10.1108/BIJ-03-2023-0196.

[73] Y. S. AlHinai, "Disaster management digitally transformed: Exploring the impact and key determinants from the UK national disaster management experience," *International Journal of Disaster Risk Reduction*, vol. 51, Dec. 2020, doi: 10.1016/j.ijdrr.2020.101851.

[74] X. Ren, S. Vashisht, G. S. Aujla, and P. Zhang, "Drone-Edge Coalesce for Energy-Aware and Sustainable Service Delivery for Smart City Applications," *Sustain Cities Soc*, vol. 77, Feb. 2022, doi: 10.1016/j.scs.2021.103505.

[75] J. Friederich, D. P. Francis, S. Lazarova-Molnar, and N. Mohamed, "A framework for data-driven digital twins for smart manufacturing," *Comput Ind*, vol. 136, Apr. 2022, doi: 10.1016/j.compind.2021.103586.

[76] M. Akbari, "Data-driven review of additive manufacturing on supply chains: Regionalization, key research themes and future directions," *Comput Ind Eng*, vol. 184, Oct. 2023, doi: 10.1016/j.cie.2023.109600.

[77] Y. K. Dwivedi *et al.*, "Climate change and COP26: Are digital technologies and information management part of the problem or the solution? An editorial reflection and call to action," *Int J Inf Manage*, vol. 63, Apr. 2022, doi: 10.1016/j.ijinfomgt.2021.102456.

[78] S. A. Khan, A. Al Rashid, and M. Koç, "Adaptive response for climate change challenges for small and vulnerable coastal area (SVCA) countries: Qatar perspective," *International Journal of Disaster Risk Reduction*, vol. 96, Oct. 2023, doi: 10.1016/j.ijdrr.2023.103969.

[79] M. H. Frederiksen, P. Wolf, and U. Klotz, "Citizen visions of drone uses and impacts in 2057: Far-future insights for policy decision-makers," *Technol Forecast Soc Change*, vol. 204, Jul. 2024, doi: 10.1016/j.techfore.2024.123438.

[80] M. A. Musarat, A. M. Khan, W. S. Alaloul, N. Blas, and S. Ayub, "Automated monitoring innovations for efficient and safe construction practices," *Results in Engineering*, vol. 22, Jun. 2024, doi: 10.1016/j.rineng.2024.102057.

[81] M. Gooroochurn, "Circular homes – An energy-water-materials nexus for community climate engagement and action at grassroots level in the built environment," *Results in Engineering*, vol. 15, Sep. 2022, doi: 10.1016/j.rineng.2022.100548.

[82] R. Kumar Singh, R. Mishra, S. Gupta, and A. A. Mukherjee, "Blockchain applications for secured and resilient supply chains: A systematic literature review and future research agenda," *Comput Ind Eng*, vol. 175, Jan. 2023, doi: 10.1016/j.cie.2022.108854.

[83] A. Hauashdh, S. Nagapan, J. Jailani, and Y. Gamil, "An integrated framework for sustainable and efficient building maintenance operations aligning with climate change, SDGs, and emerging technology," *Results in Engineering*, vol. 21, Mar. 2024, doi: 10.1016/j.rineng.2024.101822.

[84] M. A. Musarat, W. S. Alaloul, A. M. Khan, S. Ayub, and N. Jousseaume, "A survey-based approach of framework development for improving the application of internet of things in the construction industry of Malaysia," *Results in Engineering*, vol. 21, Mar. 2024, doi: 10.1016/j.rineng.2024.101823.

[85] A. Kumar Singh, V. R. P. Kumar, G. Dehdasht, S. R. Mohandes, P. Manu, and F. Pour Rahimian, "Investigating the barriers to the adoption of blockchain technology in sustainable construction projects," *J Clean Prod*, vol. 403, Jun. 2023, doi: 10.1016/j.jclepro.2023.136840.

[86] R. S. Shojaei and G. Burgess, "Non-technical inhibitors: Exploring the adoption of digital innovation in the UK construction industry," *Technol Forecast Soc Change*, vol. 185, Dec. 2022, doi: 10.1016/j.techfore.2022.122036.

[87] C. T. Pérez, D. B. Costa, and M. Farragher, "Construction 4.0 case studies," in *Construction 4.0*, Routledge, 2020, pp. 421–440. doi: 10.1201/9780429398100-21.

[88] H. Amoozad Mahdiraji, F. Yaftiyan, A. Abbasi-Kamardi, and J. A. Garza-Reyes, "Investigating potential interventions on disruptive impacts of Industry 4.0 technologies in circular supply chains: Evidence from SMEs of an emerging economy," *Comput Ind Eng*, vol. 174, Dec. 2022, doi: 10.1016/j.cie.2022.108753.

[89] M. M. Nuttah, P. Roma, G. Lo Nigro, and G. Perrone, “Understanding blockchain applications in Industry 4.0: From information technology to manufacturing and operations management,” *J Ind Inf Integr*, vol. 33, Jun. 2023, doi: 10.1016/j.jii.2023.100456.

[90] A. Faccia, V. Pandey, and C. Banga, “Is Permissioned Blockchain the Key to Support the External Audit Shift to Entirely Open Innovation Paradigm?,” *Journal of Open Innovation: Technology, Market, and Complexity*, vol. 8, no. 2, Jun. 2022, doi: 10.3390/joitmc8020085.

[91] F. Costa, S. Frecassetti, M. Rossini, and A. Portioli-Staudacher, “Industry 4.0 digital technologies enhancing sustainability: Applications and barriers from the agricultural industry in an emerging economy,” *J Clean Prod*, vol. 408, Jul. 2023, doi: 10.1016/j.jclepro.2023.137208.

[92] A. Arya and R. Kansal, “Analysing Delays of Construction Projects in India: Causes and Effects,” 2016. [Online]. Available: www.ijste.org

[93] S. Sreelakshmi, B. S. Kantilal, and M. Roshan, “Boda Sagar Kantilal, Mohamed Roshan and S Gopinath, A Study on the Barriers to the Implementation of Building Information Modeling,” *International Journal of Civil Engineering and Technology*, vol. 8, no. 5, pp. 42–50, 2017, [Online]. Available: http://iaeme.com/Home/issue/IJCIET?Volume=8&Issue=5http://iaeme.com/Home/issue/IJCIET?Volume=8&Issue=5http://iaeme.com/Home/journal/IJCIET43

[94] S. Scipioni, G. Dini, and F. Niccolini, “Exploring circular shipbuilding: A systematic review on circular economy business models and supporting technologies,” *J Clean Prod*, vol. 422, Oct. 2023, doi: 10.1016/j.jclepro.2023.138470.

[95] V. Thakur, “Framework for PESTEL dimensions of sustainable healthcare waste management: Learnings from COVID-19 outbreak,” *J Clean Prod*, vol. 287, Mar. 2021, doi: 10.1016/j.jclepro.2020.125562.

[96] J. R. Surya and M. Kranti Kumar, “Barriers for Adoption of Integrated Project Delivery in Indian Construction Industry”, doi: 10.35940/ijmh.G1454.038722.

[97] S. Siriwardhana and R. C. Moehler, “Enabling productivity goals through construction 4.0 skills: Theories, debates, definitions,” *J Clean Prod*, vol. 425, Nov. 2023, doi: 10.1016/j.jclepro.2023.139011.

[98] D. Askerbekov, J. A. Garza-Reyes, R. Roy Ghatak, R. Joshi, J. Kandasamy, and D. Luiz de Mattos Nascimento, “Embracing drones and the Internet of drones systems in manufacturing – An exploration of obstacles,” *Technol Soc*, vol. 78, Sep. 2024, doi: 10.1016/j.techsoc.2024.102648.

[99] S. Jane Fox, “Drones: Foreseeing a ‘risky’ business?Policing the challenge that flies above,” *Technol Soc*, vol. 71, Nov. 2022, doi: 10.1016/j.techsoc.2022.102089.

[100] P. A. Mahendra, J. R. Pitroda, and J. J. Bhavsar, “A Study of Risk Management Techniques for Construction Projects in Developing Countries,” 2013.

[101] K. G. Engås, J. Z. Raja, and I. F. Neufang, "Decoding technological frames: An exploratory study of access to and meaningful engagement with digital technologies in agriculture," *Technol Forecast Soc Change*, vol. 190, May 2023, doi: 10.1016/j.techfore.2023.122405.

[102] A. Sasi Kumar and K. Divakar, "Critical Causes of Failure in Contracts in Indian Construction Projects," 2018. [Online]. Available: www.ijisrt.com543

[103] E. Forcael, I. Ferrari, A. Opazo-Vega, and J. Pulido Arcas, "Construction 4.0: A Literature Review," *Sustainability*, vol. 12, p. 9755, Nov. 2020, doi: 10.3390/su12229755.

[104] P. Hoonakker, P. Carayon, and T. Loushine, "Barriers and benefits of quality management in the construction industry: An empirical study," *Total Quality Management and Business Excellence*, vol. 21, no. 9, pp. 953–969, 2010, doi: 10.1080/14783363.2010.487673.

[105] A. O. Mathew, A. N. Jha, A. K. Lingappa, and P. Sinha, "Attitude towards drone food delivery services—role of innovativeness, perceived risk, and green image," *Journal of Open Innovation: Technology, Market, and Complexity*, vol. 7, no. 2, 2021, doi: 10.3390/joitmc7020144.

[106] A. L. Balogun *et al.*, "Assessing the Potentials of Digitalization as a Tool for Climate Change Adaptation and Sustainable Development in Urban Centres," *Sustain Cities Soc*, vol. 53, Feb. 2020, doi: 10.1016/j.scs.2019.101888.

[107] V. V. Krishna, "A I and contemporary challenges: The good, bad and the scary," *Journal of Open Innovation: Technology, Market, and Complexity*, vol. 10, no. 1, Mar. 2024, doi: 10.1016/j.joitmc.2023.100178.

[108] K. H. Tey, M. Y. Aminah, I. Syuhaida, and F. W. Lee, "A conceptual study Of key barriers in construction project coordination," in *Creating Global Competitive Economies: A 360-Degree Approach - Proceedings of the 17th International Business Information Management Association Conference, IBIMA 2011*, International Business Information Management Association, IBIMA, 2011, pp. 325–332. doi: 10.5171/2012.795679.

[109] S. P. Wanjari and G. Dobariya, "Identifying factors causing cost overrun of the construction projects in India," *Sadhana - Academy Proceedings in Engineering Sciences*, vol. 41, no. 6, pp. 679–693, Jun. 2016, doi: 10.1007/s12046-016-0498-3.

[110] R. Imtiaz, N. A. Memon, A. Hameed Memon, S. A. Mallah, and S. Ali, "COMMON BARRIERS TO THE IMPLEMENTATION OF AUTOMATION IN THE CONSTRUCTION PROJECTS OF SINDH," 1560. [Online]. Available: www.irjmets.com

[111] A. Ali, "Risk Factors That Leading to Cost and Time Overrun in Mega Construction Projects in Malaysia," 2018. [Online]. Available: http://abcreal.weebly.com/

[112] M. Williamson, A. Ganah, and G. A. John, "Barriers to adopting modern methods of construction in the UK," *Journal of Construction Engineering, Management & Innovation*, vol. 2, no. 1, pp. 30–39, Mar. 2019, doi: 10.31462/jcemi.2019.01030039.

[113] J. B. H. Yap, C. G. Y. Lam, M. Skitmore, and N. Talebian, “BARRIERS TO THE ADOPTION OF NEW SAFETY TECHNOLOGIES IN CONSTRUCTION: A DEVELOPING COUNTRY CONTEXT,” *Journal of Civil Engineering and Management*, vol. 28, no. 2, pp. 120–133, Jan. 2022, doi: 10.3846/jcem.2022.16014.

[114] H. A. Rani, A. M. Farouk, K. S. Anandh, S. Almutairi, and R. A. Rahman, “Impact of COVID-19 on Construction Projects: The Case of India,” *Buildings*, vol. 12, no. 6, Jun. 2022, doi: 10.3390/buildings12060762.

[115] I. Othman, A. F. Kineber, A. E. Oke, T. Zayed, and M. K. Buniya, “Barriers of value management implementation for building projects in Egyptian construction industry,” *Ain Shams Engineering Journal*, vol. 12, no. 1, pp. 21–30, Mar. 2021, doi: 10.1016/j.asej.2020.08.004.

[116] I. C. Osuizugbo, O. Oyeyipo, A. Lahanmi, A. Morakinyo, and O. Olaniyi, “Barriers to the adoption of sustainable construction,” *European Journal of Sustainable Development*, vol. 9, no. 2, pp. 150–162, Jun. 2020, doi: 10.14207/ejsd.2020.v9n2p150.

[117] R. A. Ojelabi, O. O. Oyeyipo, A. O. Afolabi, and I. O. Omuh, “Evaluating barriers inhibiting investors participation in Public-Private Partnership project bidding process using structural equation model,” *International Journal of Construction Management*, vol. 22, no. 16, pp. 3055–3064, 2022, doi: 10.1080/15623599.2020.1840010.

[118] K. F. Ne’Matullah, L. S. Pek, and S. A. Roslan, “Investigating communicative barriers on construction industry productivity in Malaysia: An overview,” *International Journal of Evaluation and Research in Education*, vol. 10, no. 2, pp. 476–482, 2021, doi: 10.11591/ijere.v10i2.21163.

[119] L. Gharaibeh, S. T. Matarneh, K. Eriksson, and B. Lantz, “An Empirical Analysis of Barriers to Building Information Modelling (BIM) Implementation in Wood Construction Projects: Evidence from the Swedish Context,” *Buildings*, vol. 12, no. 8, Aug. 2022, doi: 10.3390/buildings12081067.

[120] M. Ershadi, M. Jefferies, P. Davis, and M. Mojtahedi, “Barriers to achieving sustainable construction project procurement in the private sector,” *Clean Eng Technol*, vol. 3, Jul. 2021, doi: 10.1016/j.clet.2021.100125.

[121] M. Er, “A Holistic View of Barriers to Innovation in Australian Construction,” *International Journal of Engineering and Technology*, pp. 22–26, May 2020, doi: 10.7763/IJET.2020.V12.1178.

[122] M. Bartake, Y. S. Patil, and R. M. Swamy, “Study of Barriers in Implementing ICT in Indian Construction Industry,” 2019. [Online]. Available: www.rsisinternational.org

[123] W. S. Alaloul, M. S. Liew, N. A. W. A. Zawawi, and I. B. Kennedy, “Industrial Revolution 4.0 in the construction industry: Challenges and opportunities for stakeholders,” *Ain Shams Engineering Journal*, vol. 11, no. 1, pp. 225–230, Mar. 2020, doi: 10.1016/j.asej.2019.08.010.

[124] A. Karmakar and V. S. K. Delhi, “Construction 4.0: What we know and where we are headed?,” Jul. 01, 2021, *International Council for Research and Innovation in Building and Construction*. doi: 10.36680/j.itcon.2021.028.

[125] A. Sawhney, M. Riley, J. Irizarry, and C. Toca Pérez, “A Proposed Framework for Construction 4.0 Based on a Review of Literature.”

[126] D. Wang, Y. Dong, Y. Pan, and R. Ma, “Machine vision-based monitoring methodology for the fatigue cracks in U-Rib-to-deck weld seams,” *IEEE Access*, vol. 8, pp. 94204–94219, 2020, doi: 10.1109/ACCESS.2020.2995276.

[127] D. T. Matt, M. Molinaro, G. Orzes, and G. Pedrini, “The role of innovation ecosystems in Industry 4.0 adoption,” *Journal of Manufacturing Technology Management*, vol. 32, no. 9, pp. 369–395, 2021, doi: 10.1108/JMTM-04-2021-0119.

[128] S. Demirkesen and A. Tezel, “Investigating major challenges for industry 4.0 adoption among construction companies,” *Engineering, Construction and Architectural Management*, vol. 29, no. 3, pp. 1470–1503, Mar. 2022, doi: 10.1108/ECAM-12-2020-1059.

[129] A. Fallahpour, M. Yazdani, A. Mohammed, and K. Y. Wong, “Green sourcing in the era of industry 4.0: towards green and digitalized competitive advantages,” *Industrial Management and Data Systems*, vol. 121, no. 9, pp. 1997–2025, Sep. 2021, doi: 10.1108/IMDS-06-2020-0343.

[130] C. Newman, D. Edwards, I. Martek, J. Lai, W. D. Thwala, and I. Rillie, “Industry 4.0 deployment in the construction industry: a bibliometric literature review and UK-based case study,” *Smart and Sustainable Built Environment*, vol. 10, no. 4, pp. 557–580, Nov. 2021, doi: 10.1108/SASBE-02-2020-0016.

[131] T. O. Osunsanmi, C. O. Aigbavboa, A. Emmanuel Oke, and M. Liphadzi, “Appraisal of stakeholders’ willingness to adopt construction 4.0 technologies for construction projects,” *Built Environment Project and Asset Management*, vol. 10, no. 4, pp. 547–565, Sep. 2020, doi: 10.1108/BEPAM-12-2018-0159.

[132] T. D. Patel, T. C. Haupt, and T. Bhatt, “Fuzzy probabilistic approach for risk assessment of BOT toll roads in Indian context,” *Journal of Engineering, Design and Technology*, vol. 18, no. 1, pp. 251–269, Jan. 2020, doi: 10.1108/JEDT-05-2019-0138.

[133] P. Dallasega, “Industry 4.0 fostering construction supply chain management: Lessons learned from engineer-to-order suppliers,” *IEEE Engineering Management Review*, vol. 46, no. 3, pp. 49–55, 2018, doi: 10.1109/EMR.2018.2861389.

[134] Z. Liu, Y. Cao, L. Cui, J. Song, and G. Zhao, “A Benchmark Database and Baseline Evaluation for Fall Detection Based on Wearable Sensors for the Internet of Medical Things Platform,” *IEEE Access*, vol. 6, pp. 51286–51296, Sep. 2018, doi: 10.1109/ACCESS.2018.2869833.

[135] D. O. Aghimien, C. O. Aigbavboa, and A. E. Oke, “Critical success factors for digital partnering of construction organisations – a Delphi study,” *Engineering, Construction and Architectural Management*, vol. 27, no. 10, pp. 3171–3188, Oct. 2020, doi: 10.1108/ECAM-11-2019-0602.

[136] Z. Engin and P. Treleaven, “Algorithmic Government: Automating Public Services and Supporting Civil Servants in using Data Science Technologies,” *Computer Journal*, vol. 62, no. 3, pp. 448–460, Mar. 2019, doi: 10.1093/comjnl/bxy082.

[137] Y. Wang, J. Shi, and G. Qu, “Research on collaborative innovation cooperation strategies of manufacturing digital ecosystem from the perspective of multiple stakeholders,” *Comput Ind Eng*, vol. 190, Apr. 2024, doi: 10.1016/j.cie.2024.110003.

[138] M. Spaltini, S. Terzi, and M. Taisch, “Development and implementation of a roadmapping methodology to foster twin transition at manufacturing plant level,” *Comput Ind*, vol. 154, Jan. 2024, doi: 10.1016/j.compind.2023.104025.

[139] S. H. Alyami, A. A. Almutlaqa, A. M. Alqahtany, and N. Ashraf, “Likelihood of Reaching Zero Energy Building Design in Hot Dry Climate: Saudi Arabia,” *IEEE Access*, vol. 9, pp. 167054–167066, 2021, doi: 10.1109/ACCESS.2021.3134365.

[140] I. Akhtar, S. Kirmani, M. Suhail, and M. Jameel, “Advanced Fuzzy-Based Smart Energy Auditing Scheme for Smart Building Environment with Solar Integrated Systems,” *IEEE Access*, vol. 9, pp. 97718–97728, 2021, doi: 10.1109/ACCESS.2021.3095413.

[141] J. Kim and D. J. Shin, “A Nonuniform-Quantized Successive Cancellation Decoding of Polar Codes over AWGN Channels,” *IEEE Access*, vol. 9, pp. 80221–80235, 2021, doi: 10.1109/ACCESS.2021.3084627.

[142] S. A. Shah, D. Z. Seker, M. M. Rathore, S. Hameed, S. Ben Yahia, and D. Draheim, “Towards Disaster Resilient Smart Cities: Can Internet of Things and Big Data Analytics Be the Game Changers?,” *IEEE Access*, vol. 7, pp. 91885–91903, 2019, doi: 10.1109/ACCESS.2019.2928233.

[143] O. Blanco-Novoa, T. M. Fernandez-Carames, P. Fraga-Lamas, and M. A. Vilar-Montesinos, “A Practical Evaluation of Commercial Industrial Augmented Reality Systems in an Industry 4.0 Shipyard,” *IEEE Access*, vol. 6, pp. 8201–8218, Feb. 2018, doi: 10.1109/ACCESS.2018.2802699.

[144] A. Bajpai and S. C. Misra, “A framework for continuation of digitalization in construction: a PLS-SEM approach,” *Engineering, Construction and Architectural Management*, vol. 30, no. 10, pp. 4715–4734, Nov. 2023, doi: 10.1108/ECAM-03-2022-0230.

[145] C. McCarthy *et al.*, “A Field Study of Internet of Things-Based Solutions for Automatic Passenger Counting,” *IEEE Open Journal of Intelligent Transportation Systems*, vol. 2, pp. 384–401, 2021, doi: 10.1109/OJITS.2021.3111052.

[146] L. Hu, G. Sun, and Y. Ren, “CoEdge: Exploiting the Edge-Cloud Collaboration for Faster Deep Learning,” *IEEE Access*, vol. 8, pp. 100533–100541, 2020, doi: 10.1109/ACCESS.2020.2995583.

[147] L. Xie, Y. Ding, H. Yang, and X. Wang, “Blockchain-based secure and trustworthy internet of things in SDN-enabled 5G-VANETs,” *IEEE Access*, vol. 7, pp. 56656–56666, 2019, doi: 10.1109/ACCESS.2019.2913682.

[148] M. Suhail, I. Akhtar, S. Kirmani, and M. Jameel, “Development of Progressive Fuzzy Logic and ANFIS Control for Energy Management of Plug-In Hybrid Electric Vehicle,” *IEEE Access*, vol. 9, pp. 62219–62231, 2021, doi: 10.1109/ACCESS.2021.3073862.

[149] Y. Chen, D. Huang, Z. Liu, M. Osmani, and P. Demian, “Construction 4.0, Industry 4.0, and Building Information Modeling (BIM) for Sustainable Building Development within the Smart City,” *Sustainability (Switzerland)*, vol. 14, no. 16, Aug. 2022, doi: 10.3390/su141610028.

[150] Y. Xiang *et al.*, “Fast CRDNN: Towards on Site Training of Mobile Construction Machines,” *IEEE Access*, vol. 9, pp. 124253–124267, 2021, doi: 10.1109/ACCESS.2021.3110288.

[151] C. Aguzzi, L. Gigli, L. Sciullo, A. Trotta, and M. Di Felice, “From Cloud to Edge: Seamless Software Migration at the Era of the Web of Things,” *IEEE Access*, vol. 8, pp. 228118–228135, 2020, doi: 10.1109/ACCESS.2020.3045632.

[152] H. T. Yau, S. D. Prior, Y. Wang, and Y. Li, “IEEE Access Special Section Editorial: Advanced Artificial Intelligence Technologies for Smart Manufacturing,” 2021, *Institute of Electrical and Electronics Engineers Inc.* doi: 10.1109/ACCESS.2021.3106717.

[153] S. Rastogi, “CONSTRUCTION 4.0: THE 4 th GENERATION REVOLUTION Supply challenges and rationalization needs in complex production environments View project,” 2019. [Online]. Available: https://www.researchgate.net/publication/331131645

[154] L. Gharaibeh, K. M. Eriksson, B. Lantz, S. Matarneh, and F. Elghaish, “Toward digital construction supply chain-based Industry 4.0 solutions: scientometric-thematic analysis,” *Smart and Sustainable Built Environment*, vol. 13, no. 1, pp. 42–62, Jan. 2024, doi: 10.1108/SASBE-12-2021-0224.

[155] A. Rahman, M. K. Nasir, Z. Rahman, A. Mosavi, S. Shahab, and B. Minaei-Bidgoli, “DistBlockBuilding: A Distributed Blockchain-Based SDN-IoT Network for Smart Building Management,” *IEEE Access*, vol. 8, pp. 140008–140018, 2020, doi: 10.1109/ACCESS.2020.3012435.

[156] L. Chenya, E. Aminudin, S. Mohd, and L. S. Yap, “Intelligent Risk Management in Construction Projects: Systematic Literature Review,” *IEEE Access*, vol. 10, pp. 72936–72954, 2022, doi: 10.1109/ACCESS.2022.3189157.

[157] M. Talebkhah, A. Sali, M. Marjani, M. Gordan, S. J. Hashim, and F. Z. Rokhani, “IoT and Big Data Applications in Smart Cities: Recent Advances, Challenges, and Critical Issues,” *IEEE Access*, vol. 9, pp. 55465–55484, Jan. 2021, doi: 10.1109/ACCESS.2021.3070905.

[158] Q. Xie, X. Zhou, J. Wang, X. Gao, X. Chen, and L. Chun, “Matching Real-World Facilities to Building Information Modeling Data Using Natural Language Processing,” *IEEE Access*, vol. 7, pp. 119465–119475, 2019, doi: 10.1109/ACCESS.2019.2937219.

[159] F. Wang, J. Ma, G. Han, L. Dong, and D. Sun, “Investigating Factors Influencing Moment Tensor Inversion of Induced Seismicity in Virtual IoT,” *IEEE Access*, vol. 7, pp. 34238–34251, 2019, doi: 10.1109/ACCESS.2019.2902627.

[160] M. Sidorov, P. V. Nhut, Y. Matsumoto, and R. Ohmura, “LoRa-Based Precision Wireless Structural Health Monitoring System for Bolted Joints in a Smart City Environment,” *IEEE Access*, vol. 7, pp. 179235–179251, 2019, doi: 10.1109/ACCESS.2019.2958835.

[161] P. Das, S. Perera, S. Senaratne, and R. Osei-Kyei, "Paving the way for industry 4.0 maturity of construction enterprises: a state of the art review," *Engineering, Construction and Architectural Management*, vol. 30, no. 10, pp. 4665–4694, Nov. 2023, doi: 10.1108/ECAM-11-2021-1001.

[162] M. Nemati, Y. H. Kim, and J. Choi, "Toward Joint Radar, Communication, Computation, Localization, and Sensing in IoT," *IEEE Access*, vol. 10, pp. 11772–11788, 2022, doi: 10.1109/ACCESS.2022.3146830.

[163] B. Godager, E. Onstein, and L. Huang, "The Concept of Enterprise BIM: Current Research Practice and Future Trends," *IEEE Access*, vol. 9, pp. 42265–42290, 2021, doi: 10.1109/ACCESS.2021.3065116.

[164] S. Qazi, B. A. Khawaja, and Q. U. Farooq, "IoT-Equipped and AI-Enabled Next Generation Smart Agriculture: A Critical Review, Current Challenges and Future Trends," 2022, *Institute of Electrical and Electronics Engineers Inc.* doi: 10.1109/ACCESS.2022.3152544.

[165] D. Quick and K. K. R. Choo, "IoT Device Forensics and Data Reduction," *IEEE Access*, vol. 6, pp. 47566–47574, Aug. 2018, doi: 10.1109/ACCESS.2018.2867466.

[166] D. Calvetti, P. Mêda, H. de Sousa, M. C. Gonçalves, J. M. A. Faria, and J. M. da Costa, "Experiencing Education 5.0 for Civil Engineering," in *Procedia Computer Science*, Elsevier B.V., 2024, pp. 2416–2425. doi: 10.1016/j.procs.2024.02.060.

[167] C. Boton, L. Rivest, O. Ghnaya, and M. Chouchen, "What is at the Root of Construction 4.0: A Systematic Review of the Recent Research Effort," *Archives of Computational Methods in Engineering*, vol. 28, no. 4, pp. 2331–2350, Jun. 2021, doi: 10.1007/s11831-020-09457-7.

[168] P. Fraga-Lamas, J. Varela-Barbeito, and T. M. Fernandez-Carames, "Next Generation Auto-Identification and Traceability Technologies for Industry 5.0: A Methodology and Practical Use Case for the Shipbuilding Industry," *IEEE Access*, vol. 9, pp. 140700–140730, 2021, doi: 10.1109/ACCESS.2021.3119775.

[169] S. Hussain, C. Z. El-Bayeh, C. Lai, and U. Eicker, "Multi-Level Energy Management Systems Toward a Smarter Grid: A Review," *IEEE Access*, vol. 9, pp. 71994–72016, 2021, doi: 10.1109/ACCESS.2021.3078082.

[170] C. Y. Chang, S. J. Gou, S. S. Hung, and Y. T. Lin, "Performance Analysis of Indoor Smart Environmental Control Factors: Using Temperature to Control the Rate of Formaldehyde Emission," *IEEE Access*, vol. 7, pp. 163749–163756, 2019, doi: 10.1109/ACCESS.2019.2950142.

[171] A. Rahman *et al.*, "SmartBlock-SDN: An Optimized Blockchain-SDN Framework for Resource Management in IoT," *IEEE Access*, vol. 9, pp. 28361–28376, 2021, doi: 10.1109/ACCESS.2021.3058244.

[172] S. Mei *et al.*, "Paving the way to smart micro energy grid: concepts, design principles, and engineering practices," *CSEE Journal of Power and Energy Systems*, vol. 3, no. 4, pp. 440–449, Dec. 2017, doi: 10.17775/CSEEJPES.2016.01930.

[173] C. Maureira, H. Pinto, V. Yepes, and J. Garcia, “Towards an AEC-AI industry optimization algorithmic knowledge mapping: An adaptive methodology for macroscopic conceptual analysis,” *IEEE Access*, vol. 9, pp. 110842–110879, 2021, doi: 10.1109/ACCESS.2021.3102215.

[174] C. J. Turner, J. Oyekan, L. Stergioulas, and D. Griffin, “Utilizing Industry 4.0 on the Construction Site: Challenges and Opportunities,” *IEEE Trans Industr Inform*, vol. 17, no. 2, pp. 746–756, Feb. 2021, doi: 10.1109/TII.2020.3002197.

[175] M. A. Mohamed Hashim, I. Tlemsani, R. Mason-Jones, R. Matthews, and V. Ndrecaj, “Higher education via the lens of industry 5.0: Strategy and perspective,” *Social Sciences and Humanities Open*, vol. 9, Jan. 2024, doi: 10.1016/j.ssaho.2024.100828.

[176] T. Seyman Guray and B. Kismet, “VR and AR in construction management research: bibliometric and descriptive analyses,” *Smart and Sustainable Built Environment*, vol. 12, no. 3, pp. 635–659, Apr. 2023, doi: 10.1108/SASBE-01-2022-0015.

[177] A. Padovano, M. Cardamone, M. Woschank, and C. Pacher, “Exploring Human-Centricity in Industry 5.0: Empirical Insights from a Social Media Discourse,” in *Procedia Computer Science*, Elsevier B.V., 2024, pp. 1859–1868. doi: 10.1016/j.procs.2024.02.008.

[178] V. Adela *et al.*, “Bookkeeping practices and SME performance: The intervening role of owners’ accounting skills,” *Heliyon*, vol. 10, no. 1, Jan. 2024, doi: 10.1016/j.heliyon.2023.e23911.

[179] V. Rodrigues, Z. Breda, and C. Rodrigues, “The implications of industry 4.0 for the tourism sector: A systematic literature review,” *Heliyon*, vol. 10, no. 11, Jun. 2024, doi: 10.1016/j.heliyon.2024.e31590.

[180] R. Riggs, C. M. Felipe, J. L. Roldán, and J. C. Real, “Information systems capabilities value creation through circular economy practices in uncertain environments: A conditional mediation model,” *J Bus Res*, vol. 175, Mar. 2024, doi: 10.1016/j.jbusres.2024.114526.

[181] A. Fathalizadeh, M. R. Hosseini, S. S. Vaezzadeh, D. J. Edwards, I. Martek, and S. Shooshtarian, “Barriers to sustainable construction project management: the case of Iran,” *Smart and Sustainable Built Environment*, vol. 11, no. 3, pp. 717–739, Nov. 2022, doi: 10.1108/SASBE-09-2020-0132.

[182] N. Imjai, S. Aujirapongpan, and Z. Yaacob, “Impact of logical thinking skills and digital literacy on Thailand’s generation Z accounting students’ internship effectiveness: Role of self-learning capability,” *International Journal of Educational Research Open*, vol. 6, Jun. 2024, doi: 10.1016/j.ijedro.2024.100329.

[183] A. Bonello, E. Francalanza, and P. Refalo, “The realities of achieving a Smart, Sustainable, and Inclusive shopfloor in the age of Industry 5.0,” in *Procedia Computer Science*, Elsevier B.V., 2024, pp. 2406–2415. doi: 10.1016/j.procs.2024.02.059.

[184] Aditi, K. Govindan, and P. C. Jha, “Modelling of barriers in implementing sustainable manufacturer-supplier collaboration and coping strategies,” *J Clean Prod*, vol. 434, Jan. 2024, doi: 10.1016/j.jclepro.2023.139635.

[185] S. H. Aldulaimi, M. Yousif, A. Keir, and M. M. Abdeldayem, “Implementing Green Human Resources Management to Promote Sustainability Development: Application from Telecommunication Companies in Kingdom of Bahrain,” *J Stat Appl Probab*, vol. 11, no. 1, pp. 321–330, Jan. 2022, doi: 10.18576/jsap/110125.

[186] S. Hameed Aldulaimi and M. Mohamed Abdeldayem, “How Changes In Leadership Behaviour And Management Influence Sustainable Higher Education In Bahrain,” *INTERNATIONAL JOURNAL OF SCIENTIFIC & TECHNOLOGY RESEARCH*, vol. 8, no. 11, 2019, [Online]. Available: www.ijstr.org

[187] A. Cavalieri, J. Reis, and M. Amorim, “Socioenvironmental assessment and application process for IOT: A comprehensive approach,” *J Clean Prod*, vol. 436, Jan. 2024, doi: 10.1016/j.jclepro.2023.140348.

[188] M. Piccarozzi, C. Silvestri, L. Fici, and L. Silvestri, “Metaverse: a possible sustainability enabler in the transition from Industry 4.0 to 5.0,” in *Procedia Computer Science*, Elsevier B.V., 2024, pp. 1839–1848. doi: 10.1016/j.procs.2024.02.006.

[189] V. C. Poschauko, E. Kreuzer, M. Hirz, and C. Pacher, “Engineering Education goes Lifelong Learning: Modularized Technical Vocational Education and Training Program for the Automotive Sector,” in *Procedia Computer Science*, Elsevier B.V., 2024, pp. 1799–1808. doi: 10.1016/j.procs.2024.02.002.

[190] E. Ozuna and L. Steinhoff, “‘Look me in the eye, customer’: How do face-to-face interactions in peer-to-peer sharing economy services affect customers’ misbehavior concealment intentions?,” *J Bus Res*, vol. 177, Apr. 2024, doi: 10.1016/j.jbusres.2024.114582.

[191] T. van Erp, N. G. P. Carvalho, M. C. Gerolamo, R. Gonçalves, N. G. M. Rytter, and B. Gladysz, “Industry 5.0: A new strategy framework for sustainability management and beyond,” *J Clean Prod*, vol. 461, Jul. 2024, doi: 10.1016/j.jclepro.2024.142271.

[192] A. Telukdarie, T. Katsumbe, H. Mahure, and K. Murulane, “Exploring the green economy – A systems thinking modelling approach,” *J Clean Prod*, vol. 436, Jan. 2024, doi: 10.1016/j.jclepro.2024.140611.

[193] R. Huang, Z. Shen, and X. Yao, “How does industrial intelligence affect total-factor energy productivity? Evidence from China’s manufacturing industry,” *Comput Ind Eng*, vol. 188, Feb. 2024, doi: 10.1016/j.cie.2024.109901.

[194] S. Calciolari, M. Cesarini, and M. Ruberti, “Sustainability disclosure in the pharmaceutical and chemical industries: Results from bibliometric analysis and AI-based comparison of financial reports,” *J Clean Prod*, vol. 447, Apr. 2024, doi: 10.1016/j.jclepro.2024.141511.

[195] O. Alshboul, R. E. Al Mamlook, A. Shehadeh, and T. Munir, “Empirical exploration of predictive maintenance in concrete manufacturing: Harnessing machine learning for enhanced equipment reliability in construction project management,” *Comput Ind Eng*, vol. 190, Apr. 2024, doi: 10.1016/j.cie.2024.110046.

[196] C. Pacher and M. Glinik, “Fostering Entrepreneurial Mindsets in Deep Tech Disciplines: Exemplary Development of a Toolkit,” in *Procedia Computer Science*, Elsevier B.V., 2024, pp. 1309–1318. doi: 10.1016/j.procs.2024.01.129.

[197] A. Lagorio and C. Cimini, “Towards 5.0 skills acquisition for students in industrial engineering: the role of learning factories,” in *Procedia Computer Science*, Elsevier B.V., 2024, pp. 317–326. doi: 10.1016/j.procs.2024.01.031.

[198] A. Martínez-Gutiérrez, J. Díez-González, H. Perez, and M. Araújo, “Towards industry 5.0 through metaverse,” *Robot Comput Integr Manuf*, vol. 89, Oct. 2024, doi: 10.1016/j.rcim.2024.102764.

[199] D. A. de J. Pacheco, I. S. Rampasso, G. S. Michels, S. M. Ali, and J. D. Hunt, “From linear to circular economy: The role of BS 8001:2017 for green transition in small business in developing economies,” *J Clean Prod*, vol. 439, Feb. 2024, doi: 10.1016/j.jclepro.2024.140787.

[200] A. Abulibdeh, E. Zaidan, and R. Abulibdeh, “Navigating the confluence of artificial intelligence and education for sustainable development in the era of industry 4.0: Challenges, opportunities, and ethical dimensions,” *J Clean Prod*, vol. 437, Jan. 2024, doi: 10.1016/j.jclepro.2023.140527.

[201] I. Masudin, N. Tsamarah, D. P. Restuputri, T. Trireksani, and H. G. Djajadikerta, “The impact of safety climate on human-technology interaction and sustainable development: Evidence from Indonesian oil and gas industry,” *J Clean Prod*, vol. 434, Jan. 2024, doi: 10.1016/j.jclepro.2023.140211.

[202] E. Ayyildiz and M. Erdogan, “Addressing the challenges of using autonomous robots for last-mile delivery,” *Comput Ind Eng*, vol. 190, Apr. 2024, doi: 10.1016/j.cie.2024.110096.

[203] P. Karapanagiotis and P. Reimers, “Why does the schooling gap close while the wage gap persists across country income comparisons?,” *J Econ Dyn Control*, vol. 159, Feb. 2024, doi: 10.1016/j.jedc.2023.104805.

[204] F. Pistolesi, M. Baldassini, and B. Lazzerini, “A human-centric system combining smartwatch and LiDAR data to assess the risk of musculoskeletal disorders and improve ergonomics of Industry 5.0 manufacturing workers,” *Comput Ind*, vol. 155, Feb. 2024, doi: 10.1016/j.compind.2023.104042.

[205] D. Kumar, G. Soni, F. Jabeen, N. Kumar Tiwari, G. Sariyer, and B. Ramtiyal, “A hybrid Bayesian approach for assessment of industry 4.0 technologies towards achieving decarbonization in manufacturing industry,” *Comput Ind Eng*, vol. 190, Apr. 2024, doi: 10.1016/j.cie.2024.110057.

[206] S. Bag, M. Sabbir Rahman, S. Ghai, S. Kumar Srivastava, R. Kumar Singh, and R. Mishra, “Unveiling the impact of carbon-neutral policies on vital resources in Industry 4.0 driven smart manufacturing: A data-driven investigation,” *Comput Ind Eng*, vol. 187, Jan. 2024, doi: 10.1016/j.cie.2023.109798.

[207] J. M. Spreitzenbarth, C. Bode, and H. Stuckenschmidt, “Designing an AI purchasing requisition bundling generator,” *Comput Ind*, vol. 155, Feb. 2024, doi: 10.1016/j.compind.2023.104043.

[208] Z. You and L. Feng, “Integration of Industry 4.0 Related Technologies in Construction Industry: A Framework of Cyber-Physical System,” *IEEE Access*, vol. 8, pp. 122908–122922, 2020, doi: 10.1109/ACCESS.2020.3007206.

[209] B. N. Pasi, S. K. Mahajan, and S. B. Rane, “Development of innovation ecosystem framework for successful adoption of industry 4.0 enabling technologies in Indian manufacturing industries,” *Journal of Science and Technology Policy Management*, vol. 13, no. 1, pp. 154–185, Feb. 2022, doi: 10.1108/JSTPM-10-2020-0148.

[210] B. N. Pasi, S. K. Mahajan, and S. B. Rane, “Enabling Technologies and Current Research Scenario of Industry 4.0: A Systematic Review,” in *Lecture Notes in Mechanical Engineering*, Springer Science and Business Media Deutschland GmbH, 2020, pp. 265–273. doi: 10.1007/978-981-15-4485-9_28.

[211] S. B. Rane, P. R. Potdar, and S. Rane, “Development of Project Risk Management framework based on Industry 4.0 technologies,” *Benchmarking*, vol. 28, no. 5, pp. 1451–1481, 2019, doi: 10.1108/BIJ-03-2019-0123.

[212] D. Aghimien, C. Aigbavboa, A. E. Oke, and J. Aliu, “Delineating the people-related features required for construction digitalisation,” *Construction Innovation*, vol. 24, no. 7, pp. 1–20, 2022, doi: 10.1108/CI-01-2022-0012.

[213] D. Aghimien, C. Aigbavboa, T. Meno, and M. Ikuabe, “Unravelling the risks of construction digitalisation in developing countries,” *Construction Innovation*, vol. 21, no. 3, pp. 456–475, 2021, doi: 10.1108/CI-02-2020-0026.

[214] N. Perrier *et al.*, “Construction 4.0: A survey of research trends,” Sep. 01, 2020, *International Council for Research and Innovation in Building and Construction*. doi: 10.36680/J.ITCON.2020.024.

[215] R. Maqbool, M. R. Saiba, and S. Ashfaq, “Emerging industry 4.0 and Internet of Things (IoT) technologies in the Ghanaian construction industry: sustainability, implementation challenges, and benefits,” *Environmental Science and Pollution Research*, vol. 30, no. 13, pp. 37076–37091, Mar. 2023, doi: 10.1007/s11356-022-24764-1.

[216] B. N. Pasi, S. K. Mahajan, and S. B. Rane, “Strategies for risk management in adopting Industry 4.0 concept in manufacturing industries,” *Journal of Science and Technology Policy Management*, vol. 14, no. 3, pp. 563–591, Apr. 2023, doi: 10.1108/JSTPM-04-2021-0057.

[217] K. Wang, F. Guo, C. Zhang, and D. Schaefer, “From Industry 4.0 to Construction 4.0: barriers to the digital transformation of engineering and construction sectors,” *Engineering, Construction and Architectural Management*, vol. 31, no. 1, pp. 136–158, Jan. 2024, doi: 10.1108/ECAM-05-2022-0383.

[218] F. Elghaish, S. T. Matarneh, D. J. Edwards, F. Pour Rahimian, H. El-Gohary, and O. Ejohwomu, “Applications of Industry 4.0 digital technologies towards a construction

circular economy: gap analysis and conceptual framework," *Construction Innovation*, vol. 22, no. 3, pp. 647–670, Jun. 2022, doi: 10.1108/CI-03-2022-0062.

[219] L. Statsenko, A. Samaraweera, J. Bakhshi, and N. Chileshe, "Construction 4.0 technologies and applications: a systematic literature review of trends and potential areas for development," Nov. 27, 2023, *Emerald Publishing*. doi: 10.1108/CI-07-2021-0135.

[220] B. Pasi, B. N. Pasi, S. K. Mahajan, and S. B. Rane, "Smart Supply Chain Management: A Perspective of Industry 4.0 Reliability Engineering Project, Improving Agility of Project View project COMPARISON OF DESIGN AND ANALYSIS OF TUBE SHEET THICKNESS BY USING UHX CODE OF ASME AND TEMA STANDARD View project Smart Supply Chain Management: A Perspective of Industry 4.0," *International Journal of Advanced Science and Technology*, vol. 29, no. 5, pp. 3016–3030, 2020, doi: 10.13140/RG.2.2.29012.01920.

[221] Y. Liu, K. Akram Hassan, M. Karlsson, O. Weister, and S. Gong, "Active Plant Wall for Green Indoor Climate Based on Cloud and Internet of Things," *IEEE Access*, vol. 6, pp. 33631–33644, Jun. 2018, doi: 10.1109/ACCESS.2018.2847440.

[222] S. Khin and D. M. H. Kee, "Factors influencing Industry 4.0 adoption," *Journal of Manufacturing Technology Management*, vol. 33, no. 3, pp. 448–467, Mar. 2022, doi: 10.1108/JMTM-03-2021-0111.

[223] A. Bajpai and S. C. Misra, "Barriers to implementing digitalization in the Indian construction industry," *International Journal of Quality and Reliability Management*, vol. 39, no. 10, pp. 2438–2464, Nov. 2022, doi: 10.1108/IJQRM-09-2020-0318.

[224] V. N. Vo, C. So-In, H. Tran, D. D. Tran, and T. P. Huu, "Performance Analysis of an Energy-Harvesting IoT System Using a UAV Friendly Jammer and NOMA under Cooperative Attack," *IEEE Access*, vol. 8, pp. 221986–222000, 2020, doi: 10.1109/ACCESS.2020.3044760.

[225] M. Kor, I. Yitmen, and S. Alizadehsalehi, "An investigation for integration of deep learning and digital twins towards Construction 4.0," *Smart and Sustainable Built Environment*, vol. 12, no. 3, pp. 461–487, Apr. 2023, doi: 10.1108/SASBE-08-2021-0148.

[226] M. Asplund and S. Nadjm-Tehrani, "Attitudes and Perceptions of IoT Security in Critical Societal Services," *IEEE Access*, vol. 4, pp. 2130–2138, 2016, doi: 10.1109/ACCESS.2016.2560919.

[227] B. N. Pasi, S. K. Mahajan, and S. B. Rane, "The current sustainability scenario of Industry 4.0 enabling technologies in Indian manufacturing industries," *International Journal of Productivity and Performance Management*, vol. 70, no. 5, pp. 1017–1048, 2020, doi: 10.1108/IJPPM-04-2020-0196.

[228] M. Fajkus *et al.*, "Fiber-optic bragg system for the dynamic weighing of municipal waste: A pilot study," *IEEE Access*, vol. 9, pp. 99050–99059, 2021, doi: 10.1109/ACCESS.2021.3095219.

[229] J. Menegon and L. C. P. da Silva Filho, "The Impact of Industry 4.0 Concepts and Technologies on Different Phases of Construction Project Lifecycle: A Literature

Review," Jun. 01, 2023, *Springer Science and Business Media Deutschland GmbH*. doi: 10.1007/s40996-022-00989-5.

[230] R. I. Ramírez Molina, M. J. Santamaria Ruiz, R. J. Ramírez Molina, N. D. Lay Raby, and P. Severino-González, "Innovation systems in industry 5.0: theoretical and methodological bases," in *Procedia Computer Science*, Elsevier B.V., 2024, pp. 595–600. doi: 10.1016/j.procs.2023.12.256.

[231] F. Fraile, T. Tagawa, R. Poler, and A. Ortiz, "Trustworthy Industrial IoT Gateways for Interoperability Platforms and Ecosystems," *IEEE Internet Things J*, vol. 5, no. 6, pp. 4506–4514, Dec. 2018, doi: 10.1109/JIOT.2018.2832041.

[232] M. M. Abdeldayem and S. H. Aldulaimi, "Sustainable Leadership and Sustainability: Insights from the GCC," in *Technical and Vocational Education and Training*, vol. 38, Springer, 2024, pp. 401–411. doi: 10.1007/978-981-99-6909-8_35.

The current issue and full text archive of this journal is available on Emerald Insight at:
https://www.emerald.com/insight/2053-4620.htm

Journal of Science and Technology Policy Management

A comprehensive overview of Construction 4.0 technologies and their implementation in the construction industry

Pallavi Dhamak
Department of Technology Management, Shri Vile Parle Kelavani Mandal Narsee Monjee Institute of Management Studies, Mukesh Patel School of Technology Management and Engineering, Mumbai, India, and Department of Civil Engineering, Vishwaniketan's Institute of Management Entrepreneurship and Engineering Technology, Navi Mumbai, India

Padmanabha Aital
Department of Technology Management, Shri Vile Parle Kelavani Mandal Narsee Monjee Institute of Management Studies, Mukesh Patel School of Technology Management and Engineering, Mumbai, India, and

Anand Daftardar
Department of Civil Engineering, Shri Vile Parle Kelavani Mandal Narsee Monjee Institute of Management Studies, Mukesh Patel School of Technology Management and Engineering, Mumbai, India

Received 23 September 2023
Revised 16 March 2024
24 August 2024
5 October 2024
Accepted 9 January 2025

Abstract

Purpose – The purpose of this study is to examine Construction 4.0 trends, identify potential areas of growth, and explore the use of Industry 4.0 enabling technologies in the construction sector.

Design/methodology/approach – Research papers from referred international journals are reviewed to identify the use of Industry 4.0 enabling technologies in the construction sector. Then, Visualization of Similarities viewer software is used to analyze the keyword co-occurrence network, overlay and density visualization. Finally, the roadmap for the adoption of the Industry 4.0 concept in the construction sector is proposed.

Findings – Thirteen technologies of the Industry 4.0 concept have an impact on the construction sector. However, Digital Twins, the internet of things, Smart Sensors and 3D printing have the potential to support the Construction 4.0 concept, whereas applications of machine learning, autonomous robotics and augmented/virtual reality still offer plenty of opportunities for future applied research.

Practical implications – This research paper will help decision-makers in the construction sector to adopt the Industry 4.0 enabling technologies. Also, it will serve as a road map for future research in Construction 4.0.

Originality/value – The literature studied for the content analysis includes the years 2013 through 2023, which aids in the development of plans by policymakers for the adoption of the digital construction sector.

Keywords Industry 4.0, Systematic literature review, Construction 4.0, Internet of things, Digital twin, Roadmap

Paper type General review

Journal of Science and Technology Policy Management
© Emerald Publishing Limited
2053-4620
DOI 10.1108/JSTPM-09-2023-0162

The current issue and full text archive of this journal is available on Emerald Insight at:
https://www.emerald.com/insight/1934-8835.htm

International Journal of Organizational Analysis

Strategic management of barriers in the adoption of Construction 4.0: TOPSIS and 5W2H approach for sustainable development goal integration

Pallavi Dhamak
Department of Technology Management, Shri Vile Parle Kelavani Mandal Narsee Monjee Institute of Management Studies, Mukesh Patel School of Technology Management and Engineering, Mumbai, India, and Department of Civil Engineering, Vishwaniketan's Institute of Management Entrepreneurship and Engineering Technology, Navi Mumbai, India

Padmanabha Aital
Department of Technology Management, Shri Vile Parle Kelavani Mandal Narsee Monjee Institute of Management Studies, Mukesh Patel School of Technology Management and Engineering, Mumbai, India, and

Anand Daftardar
Department of Civil Engineering, Shri Vile Parle Kelavani Mandal Narsee Monjee Institute of Management Studies, Mukesh Patel School of Technology Management and Engineering, Mumbai, India

Received 29 December 2024
Revised 15 March 2025
Accepted 1 May 2025

Abstract

Purpose – This study aims to identify and rank the barriers to adopting Construction 4.0 and to evaluate the effectiveness of practical strategies for overcoming these challenges, focusing on sustainable development goals (SDGs), technological integration and safety considerations.

Design/methodology/approach – This research paper identifies barriers related to the adoption of Construction 4.0 in the construction industry through a literature review of peerreviewed journal articles and construction industry experts. The study uses the Technique for Order of Preference by Similarity to the Ideal Solution (TOPSIS) to systematically evaluate and rank barriers to the adoption of Construction 4.0. Data were gathered through expert surveys, providing insights from experienced professionals within the construction industry. Then, the strategies were proposed and their effectiveness was evaluated. Also, these strategies were mapped with barriers and SDGs via the 5W2H (i.e., What, Why, Where, When, Who, How, and How Much) approach. Finally, a systematic framework for barrier management was proposed.

Findings – Results indicate that high initial cost and internal communication issues are the top-ranked barriers, followed closely by project management inefficiencies, lack of funding for innovation and lack of demand. Also, the effectiveness index value for the proposed eight strategies to mitigate the identified 34 barriers is 4.6, which falls between "high effectiveness" and "very high effectiveness." The study proposes a barrier management framework, providing actionable strategies to address these high-impact barriers for smoother adoption of Construction 4.0.

Research limitations/implications – This study is limited to the perspectives of developing countries of construction sector professionals and focuses on a specific set of identified barriers. Broader generalizability may require further research across different countries or industries.

International Journal of Organizational Analysis
© Emerald Publishing Limited
1934-8835
DOI 10.1108/IJOA-12-2024-5114

The 6th International Conference on Advanced Technologies For Humanity

ICATH 2024

IEREK Springer Scopus

ECOLE MAROCAINE DES SCIENCES DE L'INGENIEUR

INSEA

INPT

Université Mohammed V Faculté des Sciences Rabat

ECOLE NATIONALE SUPERIEURE DES MINES DE RABAT

CERTIFICATE OF APPRECIATION

THIS CERTIFICATE IS PRESENTED TO

PALLAVI DHAMAK, PADMANABHA AITAL, ANAND DAFTARDAR AND BHAVESHKUMAR PASI

FOR THEIR PARTICIPATION AS **AUTHORS OF**

Preparing for Industry 5.0: Inclusive Curricular Approaches and Digital Empowerment

DURING **ICATH'24**

17-19 of July 2024, UNISA, Salerno, Italy

ICATH 2024 JULY 17 -19 SALERNO ITALY

THE 6TH INTERNATIONAL CONFERENCE ON ADVANCED TECHNOLOGIES FOR HUMANITY

AYMAN MOSALLAM

ROSA PENNA

LUCIANO FEO

BRAHIM ELBHIRI

Chapter 7
Navigating Inclusion in the Industry 4.0 Horizon:
Crafting a Pedagogical Future

Pallavi Sakhahari Dhamak
https://orcid.org/0009-0001-3229-4512
Shri Vile Parle Kelavani Mandal Narsee Monjee Institute of Management Studies, Mukesh Patel School of Technology Management and Engineering, Mumbai, India

Padmanabha Aital
Shri Vile Parle Kelavani Mandal Narsee Monjee Institute of Management Studies, Mukesh Patel School of Technology Management and Engineering, Mumbai, India

Anand Daftardar
Shri Vile Parle Kelavani Mandal Narsee Monjee Institute of Management Studies, Mukesh Patel School of Technology Management and Engineering, Mumbai, India

ABSTRACT

This study investigates the integration of Industry 4.0 technologies in education, focusing on their usage across different educational levels and their impact on learning. Through a comprehensive literature review of articles from Scopus, ScienceDirect, and Web of Science databases, 51 articles were quantitatively analysed and 23 articles were qualitatively examined. Findings highlight the increasing use of augmented reality, virtual reality, the Internet of Things, and simulations, particularly in higher education, to enhance student engagement, promote active participation, and replicate real-world scenarios. Despite their benefits, these technologies are underutilised and mostly confined to manufacturing-related courses. The study

DOI: 10.4018/979-8-3693-4058-5.ch007

Copyright © 2025, IGI Global. Copying or distributing in print or electronic forms without written permission of IGI Global is prohibited.

(12) PATENT APPLICATION PUBLICATION
(19) INDIA
(22) Date of filing of Application :09/01/2025
(21) Application No.202521002069 A
(43) Publication Date : 07/02/2025

(54) Title of the invention : AN INTERNET-OF-THINGS (IOT)-BASED WEARABLE ASSEMBLY TO MONITOR AND WARN A USER

(51) International classification :G08B21/02, A61B5/00, A42B3/00
(86) International Application No :NA
Filing Date :NA
(87) International Publication No : NA
(61) Patent of Addition to Application Number :NA
Filing Date :NA
(62) Divisional to Application Number :NA
Filing Date :NA

(71)**Name of Applicant :**
1)DHAMAK, Pallavi Sakhahari
Address of Applicant :Department of Technology Management, Shri Vile Parle Kelavani Mandal Narsee Monjee Institute of Management Studies, Mukesh Patel School of Technology Management and Engineering, V. L, Pherozeshah Mehta Road, Vile Parle West, Mumbai - 400056, Maharashtra, India Mumbai ---------- ----------
2)AITAL, Padmanabha
3)DAFTARDAR, Anand
4)RANE, Santosh B.
Name of Applicant : NA
Address of Applicant : NA
(72)**Name of Inventor :**
1)DHAMAK, Pallavi Sakhahari
Address of Applicant :Department of Technology Management, Shri Vile Parle Kelavani Mandal Narsee Monjee Institute of Management Studies, Mukesh Patel School of Technology Management and Engineering, V. L, Pherozeshah Mehta Road, Vile Parle West, Mumbai - 400056, Maharashtra, India Mumbai ---------- ----------
2)AITAL, Padmanabha
Address of Applicant :Department of Technology Management, Shri Vile Parle Kelavani Mandal Narsee Monjee Institute of Management Studies, Mukesh Patel School of Technology Management and Engineering, V. L, Pherozeshah Mehta Road, Vile Parle West, Mumbai - 400056, Maharashtra, India Mumbai ---------- ----------
3)DAFTARDAR, Anand
Address of Applicant :Department of Civil Engineering, Shri Vile Parle Kelavani Mandal Narsee Monjee Institute of Management Studies, Mukesh Patel School of Technology Management and Engineering, V. L, Pherozeshah Mehta Road, Vile Parle West, Mumbai - 400056, Maharashtra, India Mumbai ---------- ----------
4)RANE, Santosh B.
Address of Applicant :Department of Mechanical Engineering, Bhavan's Campus, Old D N Nagar, Munshi Nagar, Andheri West, Mumbai - 400058, Maharashtra, India Mumbai ---------- ----------

(57) Abstract :
The disclosure relates to internet-of-things (IoT)-based wearable assembly (100) to monitor and warn user. IoT-based wearable assembly (100) comprises head protection unit (102), hand wearable unit (106), and alert determination unit (110). Head protection unit (102), to protect the user from physical injury, comprises monitoring module (104) to monitor data associated with location-related attributes, and surrounding parameters of user. Hand wearable unit (106), coupled with the head protection unit (102), can capture physiological parameters of user in real-time. Alert determination unit (108) can receive monitored data from head protection unit (102) and captured data from hand wearable unit (106). Alert determination unit (108) can analyze monitored and captured data with respect to corresponding predetermined safety thresholds. Alert determination unit (108) can transmit alert signal to one or more other users, in response to identifying, based on analysis, an anomaly in monitored and captured data with respect to corresponding predetermined safety thresholds.

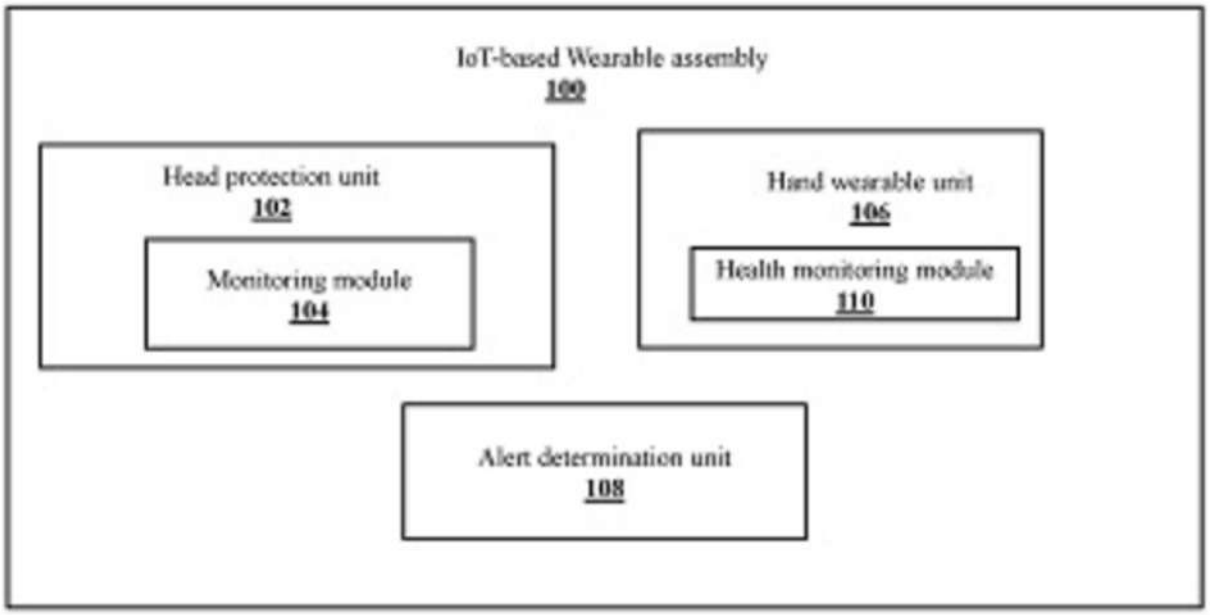


Figure 1

No. of Pages : 32 No. of Claims : 10

Source details

Journal of Science and Technology Policy Management

Formerly known as: Journal of Science and Technology Policy in China

Years currently covered by Scopus: from 2014 to 2025

Publisher: Emerald Publishing

ISSN: 2053-4620 E-ISSN: 2053-4639

Subject area: Business, Management and Accounting: Industrial Relations
Decision Sciences: Management Science and Operations Research
Business, Management and Accounting: Strategy and Management
View all

Source type: Journal

CiteScore 2023
5.9

SJR 2023
0.529

SNIP 2023
1.014

View all documents > | Set document alert | Save to source list

CiteScore | CiteScore rank & trend | Scopus content coverage

CiteScore 2023

$$5.9 = \frac{855 \text{ Citations } 2020 - 2023}{145 \text{ Documents } 2020 - 2023}$$

Calculated on 05 May, 2024

CiteScoreTracker 2024

$$8.0 = \frac{1{,}458 \text{ Citations to date}}{183 \text{ Documents to date}}$$

Last updated on 05 April, 2025 • Updated monthly

CiteScore rank 2023

Category	Rank	Percentile
Business, Management and Accounting Industrial Relations	#11/60	82nd
Decision Sciences Management	#57/207	72nd

View CiteScore methodology > | CiteScore FAQ > | Add CiteScore to your site

Source details

International Journal of Organizational Analysis

Formerly known as: Organizational Analysis

Years currently covered by Scopus: from 2005 to 2025

Publisher: Emerald Publishing

ISSN: 1934-8835

Subject area: Business, Management and Accounting: Organizational Behavior and Human Resource Management

Business, Management and Accounting: Strategy and Management

Source type: Journal

CiteScore 2023
6.0

SJR 2023
0.822

SNIP 2023
1.534

View all documents > | Set document alert | Save to source list

CiteScore | CiteScore rank & trend | Scopus content coverage

CiteScore 2023

$$6.0 = \frac{2{,}559 \text{ Citations } 2020 - 2023}{429 \text{ Documents } 2020 - 2023}$$

Calculated on 05 May, 2024

CiteScoreTracker 2024

$$7.4 = \frac{3{,}485 \text{ Citations to date}}{469 \text{ Documents to date}}$$

Last updated on 05 April, 2025 • Updated monthly

CiteScore rank 2023

Category	Rank	Percentile
Business, Management and Accounting	#56/230	75th
Organizational Behavior and Human Resource Management		

View CiteScore methodology > | CiteScore FAQ > | Add CiteScore to your site

Source details

International Journal of Intelligent Unmanned Systems

Years currently covered by Scopus: from 2013 to 2025

Publisher: Emerald Publishing

ISSN: 2049-6427 E-ISSN: 2049-6435

Subject area: Engineering: Automotive Engineering | Economics, Econometrics and Finance: Economics and Econometrics | Engineering: Mechanical Engineering | Mathematics: Modeling and Simulation

Source type: Journal

CiteScore 2023
3.5

SJR 2023
0.267

SNIP 2023
0.419

View all documents | Set document alert | Save to source list

CiteScore | CiteScore rank & trend | Scopus content coverage

CiteScore 2023

$$3.5 = \frac{356 \text{ Citations } 2020 - 2023}{103 \text{ Documents } 2020 - 2023}$$

Calculated on 05 May, 2024

CiteScoreTracker 2024

$$2.9 = \frac{288 \text{ Citations to date}}{100 \text{ Documents to date}}$$

Last updated on 05 April, 2025 • Updated monthly

CiteScore rank 2023

Category	Rank	Percentile
Engineering └ Automotive Engineering	#43/125	66th
Economics, Econometrics and Finance └ Economics and	#264/716	63rd

View CiteScore methodology | CiteScore FAQ | Add CiteScore to your site

Source details

Asian Education and Development Studies

Years currently covered by Scopus: from 2013 to 2025

Publisher: Emerald Publishing

ISSN: 2046-3162 E-ISSN: 2046-3170

Subject area: Social Sciences: Education | Social Sciences: Development

Source type: Journal

View all documents > | Set document alert | Save to source list

CiteScore 2024
8.1

SJR 2024
0.573

SNIP 2024
0.931

CiteScore | CiteScore rank & trend | Scopus content coverage

CiteScore 2024

$$8.1 = \frac{1{,}185 \text{ Citations } 2021 - 2024}{146 \text{ Documents } 2021 - 2024}$$

Calculated on 05 May, 2025

CiteScoreTracker 2025

$$5.0 = \frac{750 \text{ Citations to date}}{149 \text{ Documents to date}}$$

Last updated on 05 September, 2025 • Updated monthly

CiteScore rank 2024

Category	Rank	Percentile
Social Sciences — Education	#99/1620	93rd
Social Sciences — Development	#22/309	93rd

View CiteScore methodology > | CiteScore FAQ > | Add CiteScore to your site

Value Added Courses Completed During Ph.D.

S.N.	Title of Course	Learning Platform	University / College / Institute	Course Duration	Course Completion Status	Grade Secured
1	How to Write and Publish a Scientific Paper authorized	Coursera	École Polytechnique, France	04 weeks	Completed in February 2023	94.66%
2	Successful Negotiation: Essential Strategies and Skills authorized	Coursera	University of Michigan, USA	07 weeks	Completed in February 2023	99.77%
3	Understanding Research Methods authorized	Coursera	University of London, England	04 weeks	Completed in February 2023	100.00%
4	Digital Manufacturing and Design authorized	Coursera	University at Buffalo, New York	07 weeks	Completed in March 2023	97.05%
5	The Construction Industry: The way forward authorized	Coursera	Columbia University, New York	05 weeks	Completed in March 2023	96.00%
6	Mastering Digital Twin	Coursera	EIT Digital	02 weeks	March 2023	100.00%
7	Digital Twin	Coursera	University of Michigan, USA	04 weeks	Completed in March 2023	99.23%
8	Industry 4.0: "Introduction to Industry 4.0 and the Industrial Internet of Things	NPTEL	IIT Kharagpur	12 weeks	Completed in April 2023	61.00%
9	Construction 4.0: The Construction of Industry	Udemy	ICAN	33 Lectures Series	Completed in April 2023	---
10	The Digital Transformation in Industry 4.0	Udemy	ICAN	21 Lectures Series	Completed in April 2023	---

Trainings Attended During Ph.D.

S.N.	Title	Organizer	Duration	Date
1	National Level Program on Industry 4.0	Shree L. R. Tiwari college of Engineering	One Week	12/12/2022 to 16/12/2022
2	National Intellectual Property Awareness Mission Programme	Intellectual Property Office and MoE's Innovation Cell, India	One Day	02/02/2023
3	Challenges and Advances in Upstream Oil and Gas Industry	AMED University	One Week	06/02/2023 to 11/02/2023
4	Research Methodology and Use of ICT Tools	P.R. Pote Patil College of Engineering & Management, Amravati (Sponsored by ISTE)	One Week	20/02/2023 to 25/02/2023
5	Innovation, Research and IPR- Journey towards Excellence	Sardar Patel College of Engineering, Mumbai	One Week	01/03/2023 to 05/03/2023

Awards and Recognitions Received for Ph.D. Research Work

- ❖ Awarded Runner Up Position in RE Student PhD-Regional Category at the IEI NMLC FCRIT Excellence Awards 2025.
- ❖ Secured Best Research Paper Award in the National Conference organized by the Vishwaniketan's iMEET on 22nd March 2024.
- ❖ Presented Ph.D. research work in the Ph.D. & New Faculty Colloquium 2024 organized by the Indian Institute of Management Mumbai during 29th-31st January 2024.
- ❖ Awarded industry research funding of INR 51,000/- for the development of a wearable safety assembly aligned with practical industrial needs and workplace safety enhancement.
- ❖ International Research Mobility:
  - ✓ Selected for Erasmus+ Research Mobility Programme with research grant of INR 2,00,000/- and attended training at University of Malaga, Spain during June-July 2023
  - ✓ Attended International Research Fellowship Program of duration 60 days (From June 2024 to July 2024) with 100% sponsorship (approximately INR 3,50,000/-) at Avignon University, France.
  - ✓ Selected for International Research Fellowship Program of duration 45 days (From June 2025 to July 2025) with 100% sponsorship (approximately INR 4,00,000/-) at Technical University of Berlin, Germany.

Vishwaniketan's Institute of Management Entrepreneurship & Engineering Technology
(ViMEET)

VISHWANIKETAN

NATIONAL CONFERENCE

RECENT TRENDS AND DEVELOPMENT IN INDUSTRY 4.0 (RTDI4- 2024)

Certificate of Appreciation

This is to certify that the paper title

Construction 4.0: A Systematic Review of Enabling Technologies and Research Trends

By

Pallavi Dhamak, Department of Technology Management, Shri Vile Parle Kelavani Mandal Narsee Monjee Institute of Management Studies, Mukesh Patel School of Technology Management and Engineering, and Department of Civil Engineering, Vishwaniketan's Institute of Management Entrepreneurship & Engineering Technology (ViMEET), Khalapur, India

Padmanabha Aital, Department of Technology Management, Shri Vile Parle Kelavani Mandal Narsee Monjee Institute of Management Studies, Mukesh Patel School of Technology Management and Engineering, Mumbai, India

Anand Daftardar, Department of Technology Management, Shri Vile Parle Kelavani Mandal Narsee Monjee Institute of Management Studies, Mukesh Patel School of Technology Management and Engineering, Mumbai, India

was presented at the National conference and Secured Rank FIRST in Track 4

held at ViMEET, Khalapur

On 22nd March 2024

Dr. Bhaveshkumar Pasi	Dr. S. B. Kadam	Dr. Vikas Shinde	Dr. B. R. Patil
Conference Convener	Conference Chairman	Conference Chairman	Conference Chairman

Certificate ID: ViMEET/ Mech/ Conference/RTDI4/ A-11

ज्ञानम् जयति सर्वत्र
IIM MUMBAI

INSTITUTE OF
INDUSTRIAL
& SYSTEMS
ENGINEERS

CERTIFICATE

THIS CERTIFICATE IS AWARDED TO

Pallavi S. Dhamak

for participating in the **Ph.D. & New Faculty Colloquium – 2024**
with the theme "***Preparing Academic & Industry Leaders for Tomorrow's Challenges***" Organized by the
Indian Institute of Management Mumbai during
29th - 31st January 2024.

Prof. Manoj K. Tiwari
Director IIM Mumbai

Prof. Bopaya Bidanda
FULBRIGHT - NEHRU SENIOR SCHOLAR, IIM MUMBAI
ERNEST ROTH PROFESSOR, UNIVERSITY OF PITTSBURGH, USA

Trans ELEVATORS
Elevating Excellence, Always...
RESIDENTIAL, COMMERCIAL & INDUSTRIAL ELEVATORS

TRANS ENGINEERS
(An ISO 9001:2015 Certified)
63, Hanuman Lane, Beside Hotel Dwarka,
Sitabuldi, Nagpur - 440012. (MS)
95799 74509, 93708 99474
transengineers.ngp@gmail.com
www.transelevators.com

Ref: TE/NGP/2024-24/CSR-Fund/191. Date: 26/12/2024

To,
Miss. Pallavi Dhamak
Principal Investigator (PI) & Research Scholar,
NMIMS-MPSTME

Team Members (Co-PIs):
Dr. Santosh B. Rane
Dr. Padmanabha Aital
Dr. Anand Daftardar

Subject: Approval of Research Funding for the Development of a Wearable Safety Assembly.

Dear Miss. Pallavi Dhamak,

We are pleased to inform you that Trans Engineers has approved a research funding of INR 51,000/- to support your research project titled "Development of a Wearable Safety Assembly for MSMEs."

We recognize the importance of this initiative in enhancing workplace safety and fostering innovation aligned with sustainable industrial growth. Your project objectives, including the development of a cost-effective wearable safety prototype and its alignment with Sustainable Development Goals (SDGs), resonate strongly with our organizational values.

The approved funding will cover:

Research materials and equipment	:	INR 20,000
Prototype development	:	INR 25,000
Documentation and reporting	:	INR 6,000

We commend your dedication to improving safety standards for MSMEs and are proud to contribute to this meaningful endeavour.

Please coordinate with our finance team and provide your account details to facilitate the necessary procedures for the fund disbursement.

We look forward to the successful implementation of your project and its positive impact on workplace safety.

For TRANS ENGINEERS

TRANS ENGINEERS NAGPUR

Sanjay Pawade
Mobile: 95799 74509

UNIVERSIDAD DE MÁLAGA | VICERRECTORADO DE MOVILIDAD Y COOPERACIÓN INTERNACIONAL

Co-funded by the Erasmus+ Programme of the European Union

CERTIFICATE

ERASMUS+ STAFF WEEK KA 171 (2022/2023)

UNIVERSITY OF MALAGA, SPAIN (Erasmus Code: E MALAGA 01)

IT IS HEREBY CERTIFIED THAT

DONGARE PALLAVI

From: VISHWANIKETAN

Attended the training activities specified under the ERASMUS+ Programme

"I International Staff Week Erasmus+ K171"

From **26/06/2023** to **30/06/2023**
At the International Relations Office

Number of hours per week (total): **30**
Number of training days (total): **5**

Malaga, 30/06/2023
Jesus Delgado Peña
Deputy Vice Rector for
International Cooperation

Edificio Rosa de Gálvez Bulevar Louis Pasteur, 35. Campus de Teatinos – Universidad de Málaga. 29071 Málaga

AVIGNON
UNIVERSITÉ

CERTIFICATE OF APPRECIATION

on project title

Aerial Innovation: A Comprehensive Review on Integration of Unmanned Aerial Vehicles in Modern Construction Practices

by

PALLAVI S. DHAMAK

presented on 24 July 2024

The Jury appreciated the outstanding and excellent work and the pedagogical and clear presentation of the above-mentioned International Research Fellow. The candidate was motivated and very serious. She should continue in this prominent successful way.

Proposed rating for the oral fellowship defense for the candidate: A++

Proposed rating for the technical part of **PALLAVI S. DHAMAK**: 18/20

CERI
CENTRE D'ENSEIGNEMENT ET DE RECHERCHE EN INFORMATIQUE
AVIGNON UNIVERSITÉ

Avignon, July 24, 2024

Abderrahim Benslimane,

Seyed Mehdi Jazayeri, Ines Carole Kombou Sihomnou and Grace Colette Tessa Masse

Avignon University

Pallavi Vivek Dongare
Taloja Phase 2 410208 NAVI MUMBAI India

Berlin, 16.04.2025

Invitation / Letter of Acceptance to the TU Berlin Summer School/Tailored Program

To the Visa Officer, the consulate general of the Federal Republic of Germany,

We hereby confirm that Pallavi Vivek Dongare is invited to take part in the TU Berlin Summer School 2025 in the role as a chaperone for the Vishwaniketan Institute, under the booking number 10799.

The program starts on 2025-06-19 and the course takes place from 2025-06-23 – 2025-07-28, at the Technische Universität Berlin, Germany.

Pallavi Vivek Dongare will accompany students from Vishwaniketan Institute while they attend the following course: Sustainable Building Design

Please find the personal details below:

Name: Pallavi Vivek Dongare
Citizenship: India
Date of Birth: 1988-07-20
Place of Birth: NAVI MUMBAI
Country of Birth: India
Passport No.: U2602749
Date of Issue: 2020-01-20
Date of Expiry: 2030-01-19

The participant will bear all the expenses related to travel, accommodation, insurance and food.

We are delighted to be able to invite Pallavi Vivek Dongare to participate in our program, and are looking forward to meeting them in Berlin in summer.

Yours sincerely,

SUMMER
TU BERLIN

Maike Leidecker
Director
TU Berlin Summer & Winter School

United Builders
(ISO 14001:2015)
Plot No 18, Hari Ashirwad CHS, Shop No 3,
Sector 15, Panvel, Maharashtra 410206

Ref. No.: Jan-2025/Digital/Safety/Project-03 Date: 29/01/2025

To,
Pallavi Dhamak
Ph.D. Research Scholar
NMIMS, Mumbai.

Subject: Acknowledgement of Project Completion.

Dear Pallavi,

We are pleased to acknowledge the successful completion of the collaborative project aimed at proposing digital solutions to enhance safety practices within the construction domain.

Your valuable research insights and contributions have led to the development of a beta-level solution that lays a strong foundation for industry adoption and further scalability. The team at United Builders sincerely appreciates your commitment, innovation, and academic rigor throughout this initiative.

We thank you for your association and look forward to potential collaborations in the future.

Warm regards,

For United Builders

Neha Kathane
Team Lead, Project Management

United Builders (ISO 14001:2015) PANVEL